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SCIENTIFIC & TECHNICAL MEMORANDUM

A Guide to Ballistic Missile Technology

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A GUIDE TO BALLISTIC MISSILE TECHNOLOGY

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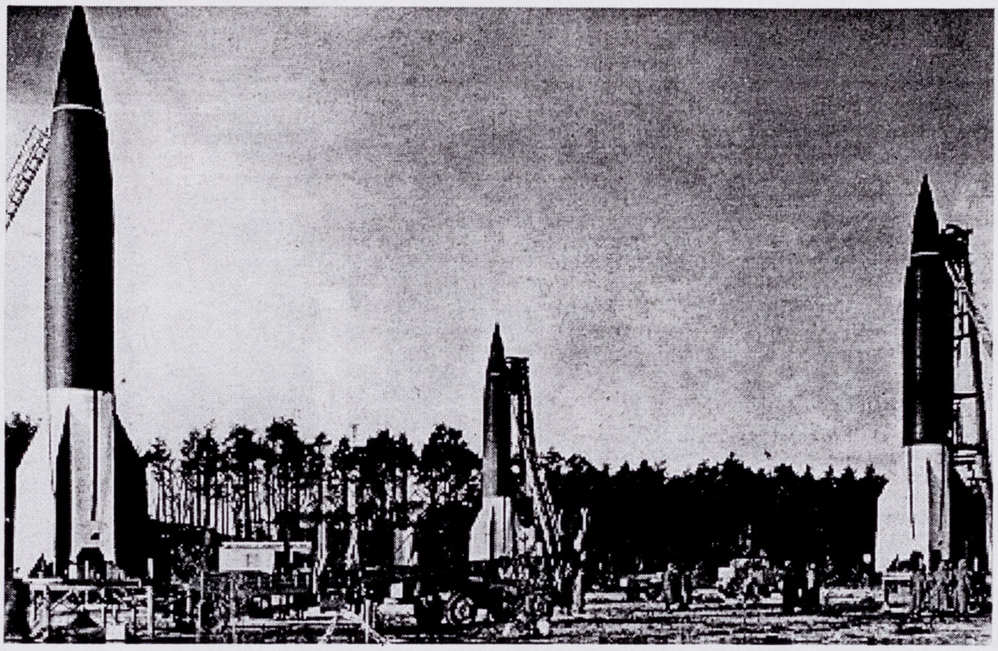


Figure 1 V-2 Missiles Being Prepared for Launch

INTRODUCTION

1. Modern ballistic missile technology has its roots in the pioneering research into rocketry carried out by amateurs, first in the USA and then in Europe, during the nineteen twenties and thirties. The recognition by the German army that an effective long range weapon might emerge from this research resulted in it being transformed into a serious programme prior to the Second World War.

2. The outcome was the development of the very successful V–2, the first 'modern' ballistic missile (Figure 1), which was fired in large numbers against London and other targets during 1944 and 1945. The V–2 had a range of 300 km and carried a one ton warhead, its design formed the basis for post–war missile construction.

3. The demonstrated effectiveness of the V–2 resulted in great enthusiasm being shown for missile development by the post war Superpowers. A missile's potential as a delivery system for the emerging nuclear weapons was soon recognised. This led to large scale missile development programmes in both the East and West in the years after 1945, and great advances were made in many associated technology areas, particularly those of engines and guidance.

4. The initial aim of each Superpower to develop a basic capability for attacking the other with nuclear tipped missiles was soon realised. Further efforts led to improved accuracy, reduced launch response times, alternative basing modes, and increased effectiveness against multiple targets. There were corresponding changes in deployment and battle strategies as each of the Superpowers sought a strategic advantage over the other.

5. Short and intermediate range missiles were also developed in large numbers and, being both land and sea based, were integrated with traditional army and navy weaponry.

6. A whole series of missiles were produced during this period, ranging from small battlefield weapons flying a few tens of kilometres, to the large multi–staged types which able to carry multiple warheads 10000 or more kilometres.

7. The possession of ballistic missile technology was also seen as an important goal by other nations due to the prestige and political influence it conferred, quite apart from any strictly military considerations. The U.K., France and China developed intermediate range ballistic missiles capable of delivering nuclear warheads (though they were not put into production in the U.K.).

8. More recently Third World countries have been acquiring missile technology, largely derived directly or indirectly from the Superpowers or China, and this spread has resulted in some destabilisation of the politics of South Asia and the Middle East. A particular threat is posed by the spread of the short range Scud-B Soviet missile amongst these nations, where it has been copied, modified and clustered. This weapon is only slightly more advanced than the wartime V-2, but with improved reliability and performance.

9. Significant indigenous missile programmes are now under way in a number of Third World countries, and a new generation of mainly short and intermediate range weapons is appearing.

10. This guide begins with a simple description of typical ballistic missiles, followed by a consideration of their advantages and the reasons for their development. This is followed by details of the trajectories they fly and the consequent aerodynamic effects.

11. The following sections, covering technology requirements, begin with a treatment of the design and construction of the missile airframe, followed by discussion of the principles of rocket propulsion. Details of the design of rocket engines suitable for ballistic missiles are then given, with coverage of propellant suitability and performance.

12. Onboard guidance and control equipment includes two basic types of instruments - gyroscopes and accelerometers, these are described together with guidance units.

13. Payload configurations and the different alternative warheads deployable on ballistic missiles are then treated, with some details of their principles of operation. The subject of re-entry vehicle design is also introduced here.

14. When comparing the technological solutions of design problems with any actual missile programme it must be borne in mind that actual progress is often constrained by practical considerations such as the availability of materials and engineering facilities, the number of skilled scientists and engineers able to work on the project, and the existence and adaptation of components from other projects or outside sources. 'Ideal' solutions to the problems of design are seldom found.

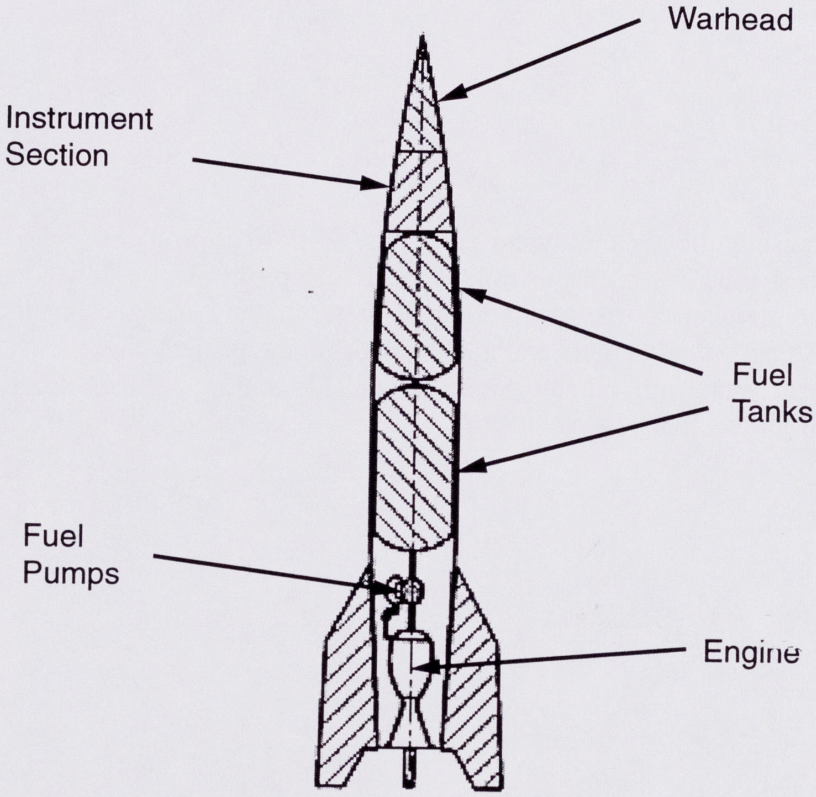


Figure 2 German V-2 Missile Construction (schematic)

BALLISTIC MISSILE FUNDAMENTALS

BASIC DESCRIPTION

– Introduction

15. A ballistic missile is a weapon which delivers a payload (or warhead) onto a distant target. This payload is mounted on the missile airframe – a roughly cylindrical rigid structure containing engines, propellant and navigation, guidance and control equipment. The construction of a simple short range missile, the wartime V–2, is shown schematically in Figure 2.

16. The ballistic missile functions to some extent like an artillery shell fired into a 'high' trajectory ('howitzer' shell). It has a much more sophisticated propulsion unit instead of the charge and, most importantly, an internal autonomous instrument based guidance and control system (as opposed to external aiming and spin stabilisation).

17. The energy required to propel the missile is contained in either solid or liquid propellants as chemical energy and converted to kinetic energy on combustion, producing high velocity exhaust gases.

18. On being launched, a ballistic missile typically rises vertically for a short while before pitching over at a small angle to aim it in the direction of the target. It accelerates rapidly until at a particular speed the engines stop, ending the 'boost' phase. The missile continues on a purely ballistic trajectory towards the target, that is, under the influence of gravity alone. The launch of a modern long–range missile is shown in Figure 3, and its nominal trajectory in figure 4.

19. A missile has to be 'steered' during flight and therefore measurements of its position, speed and direction of movement are required. Generally the steering is confined to the boost phase and leads to a vehicle attitude and position at engine cut–off that will ensure the missile, flying freely, reaches its target. Irregularities and disturbances in the attitude and motion of the missile could cause it to veer off or break up, and it is often necessary to make small changes to the missile flight to cancel out these errors.

20. At launch a ballistic missile contains all the fuels that will be needed for it to reach the target. This distinguishes it from, for instance, a cruise missile which draws fuel (air) from the atmosphere during flight.

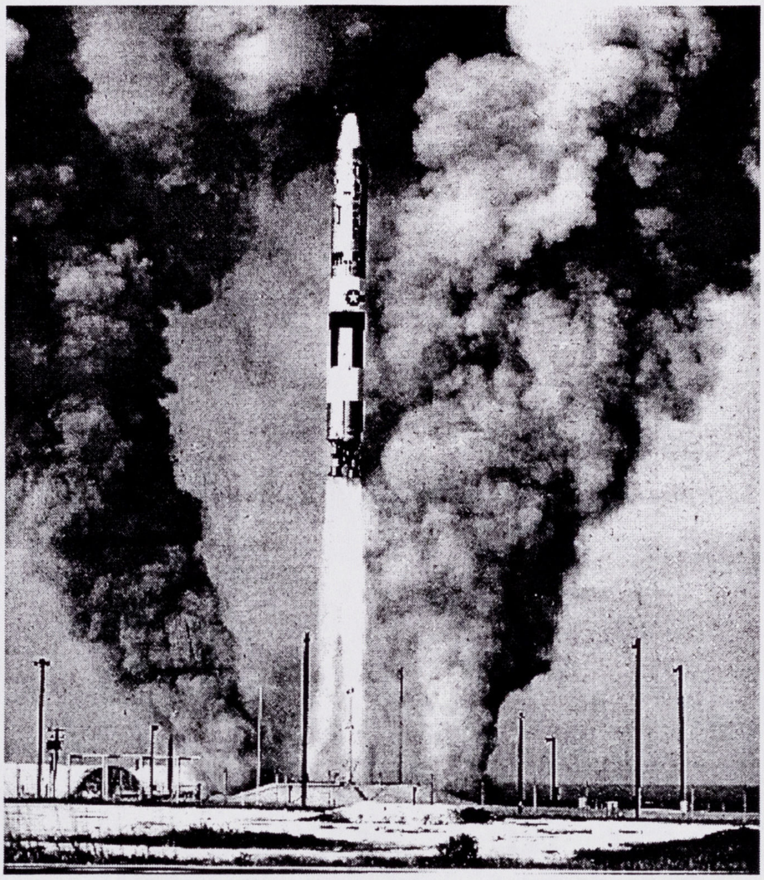


Figure 3 Titan 2 Missile Launch

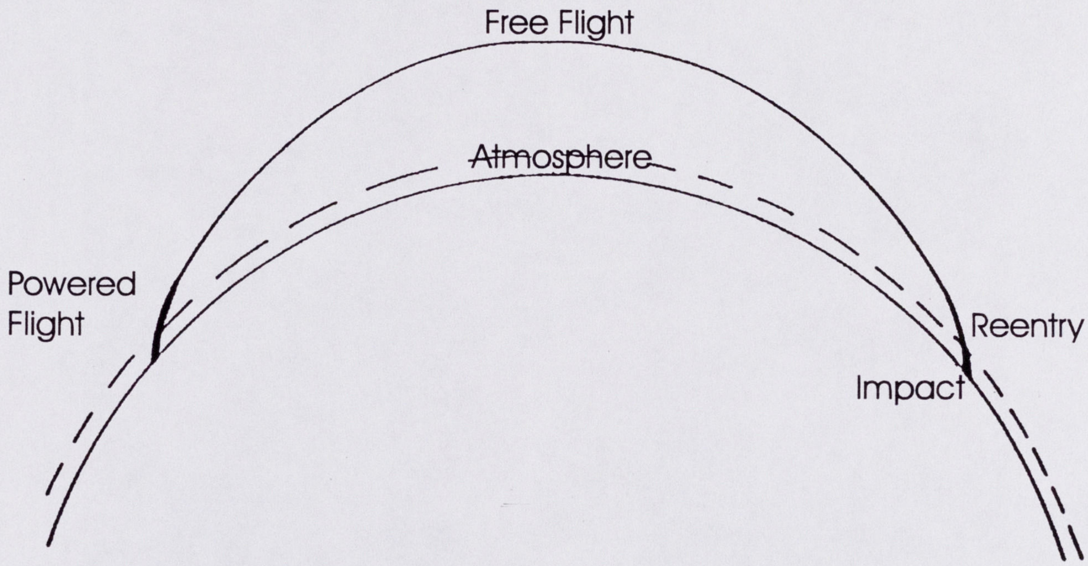


Figure 4 ICBM Nominal Trajectory

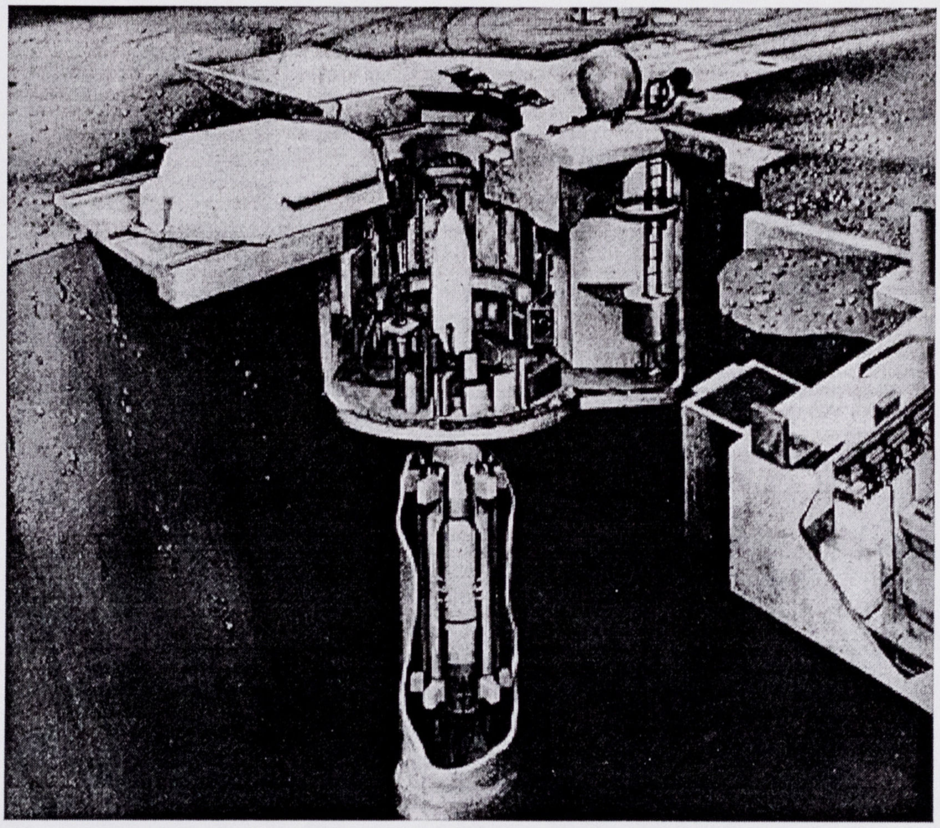


Figure 5 Minuteman 3 Silo Construction

21. Longer range missiles are usually composed of separate stages, each having engines and fuel. Once used a stage is discarded, lightening the missile. By this means, extra range is gained, though at the cost of increased missile complexity. The optimum configuration is of successively smaller second and third stages. On rare occasions as many as four stages may be used. The warhead and guidance equipment are contained in the smallest, final stage.

22. Examples of the types of ballistic missiles which have entered service since 1945 are shown in the Appendix (Figures A–1 to A–6).

23. Ballistic missiles are based, and launched, well away from the target. There are three basic classes of missiles called short, intermediate and long range or intercontinental ballistic missile, denoted SRBM, IRBM and ICBM respectively. There is no strict definition of these terms, but the 1987 Treaty between the USA and USSR covering intermediate Range Nuclear Forces (INF) gives definitions of up to 500 km, from 500 to 5500 km and greater than 5500 km for SRBMs, IRBMs and ICBMs respectively are those most widely adopted in practice.

– Main Advantages of Ballistic Missiles

24. The main advantages of ballistic missiles stem from their great separation from the target or 'war' zone prior to launch – affording security from attack, and their speed of travel – making interception extremely difficult or impossible. A principal threat is posed prior to launch by a precursor attack by other ballistic missiles, and this has led to basing in reinforced underground silos (Figure 5), on mobile launchers (trains or vehicles, Figure 6), or, since the nineteen sixties, onboard submarines.

25. Once a missile has been launched it becomes very difficult to intercept, although anti–ballistic missiles were developed and deployed by both the USA and the USSR during the seventies to counter the threat of ICBMs. The doubts which existed over their effectiveness led to the decommissioning of the US system in 1975. Even modern anti–ballistic missiles designed for use only against short range missiles, and employed as recently as the Gulf War, proved to be of questionable effectiveness.

Figure 6 Scud B Missile on a Transporter/Erector/Launcher (TEL)

THEORY OF FLIGHT

– Introduction

26. The flight path or trajectory flown by a ballistic missile is typically as shown in Figure 4a. The missile would be fired vertically and, during its initial rise, would undertake a controlled roll manoeuvre to align a guidance component axis along the azimuth direction pointing to the target.

27. After a short time a pitching manoeuvre begins, taking it on to a 'gravity turn' trajectory, where the missile axis lies along the direction of motion (or velocity vector). The sole turning moment on the missile during this period is due to gravity.

28. During the boost phase, ie whilst the propellant is burning, the missile accelerates. After engine cut–off, the parameters of which are critical to missile performance the missile follows a free–flight 'ballistic' path under the influence of gravity alone. This is in fact part of a ellipse, as seen in Figure 7a, bringing the missile back at great speed to reenter the atmosphere.

29. With short range missiles most or all of the trajectory is flown within the atmosphere, and thus, after the end of the boost phase, they are subject to aerodynamic perturbing forces. This allows positional errors to accumulate even in the relatively brief flight. Trajectories can be optimised to minimise these effects – missiles flying higher 'lofted' paths are less susceptible to them, in spite of the greater distance travelled, and have resulting higher guidance accuracies. Low angle 'depressed' trajectories are sometimes flown for operational reasons in spite of the above attendant disadvantages.

30. For longer range missiles a trajectory close to that corresponding to the well–defined minimum energy path, giving maximum range, is normally flown.

31. Sophisticated instruments sensing velocity and attitude changes are required onboard a ballistic missile to enable its position and orientation to be determined, prior to solution of the navigation, guidance and control problems.

32. For all but the shortest ranges, part of the missile trajectory will be flown outside the Earth's atmosphere (normally considered to extend to an altitude of about 70 km.) It is not unusual for a missile to be still in the boost phase at this point. Typical dynamic characteristics for missiles flying short, intermediate and long range trajectories are shown in Figure 7b (where a flat–earth approximation applies).

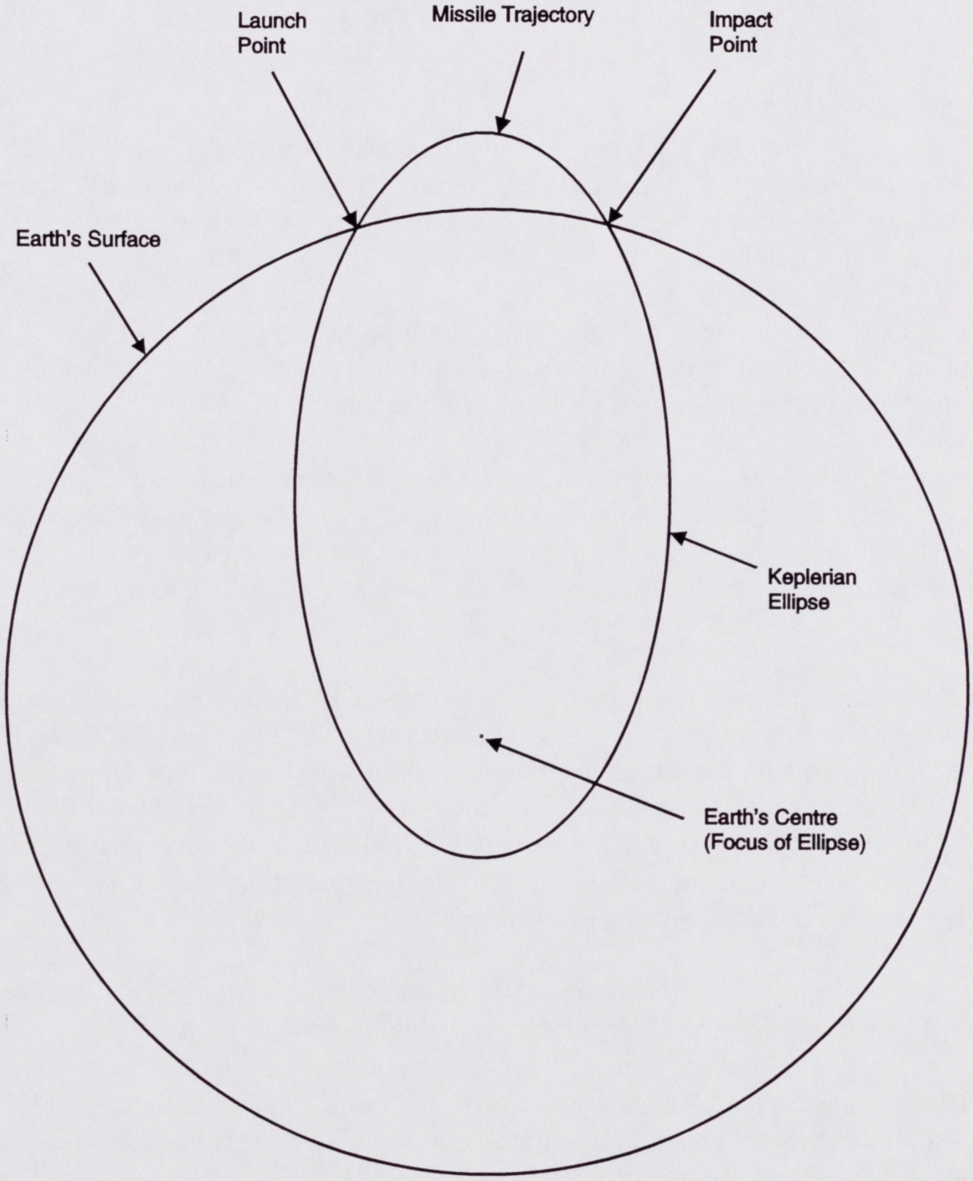


Figure 7a Missile Trajectory

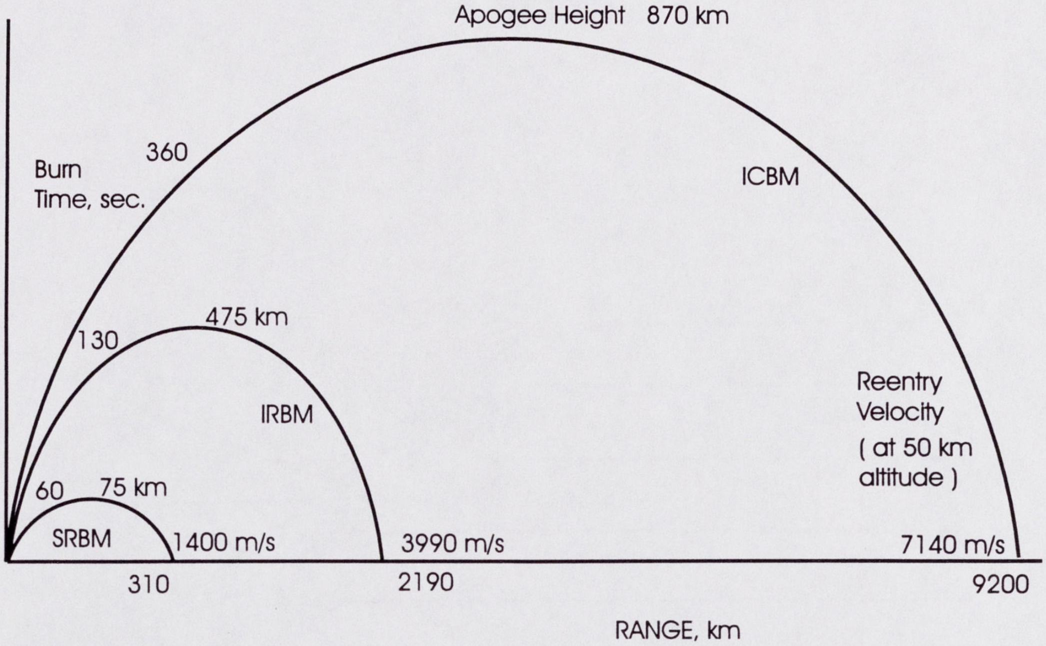


Fig 7b Typical Ballistic Missile Trajectories - Not to Scale
(Approximated to 'Flat' Earth case)

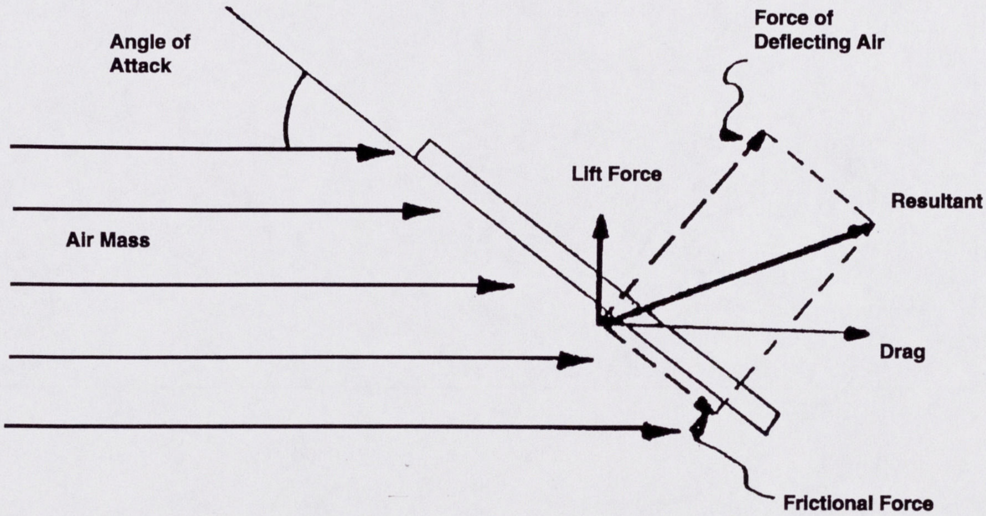
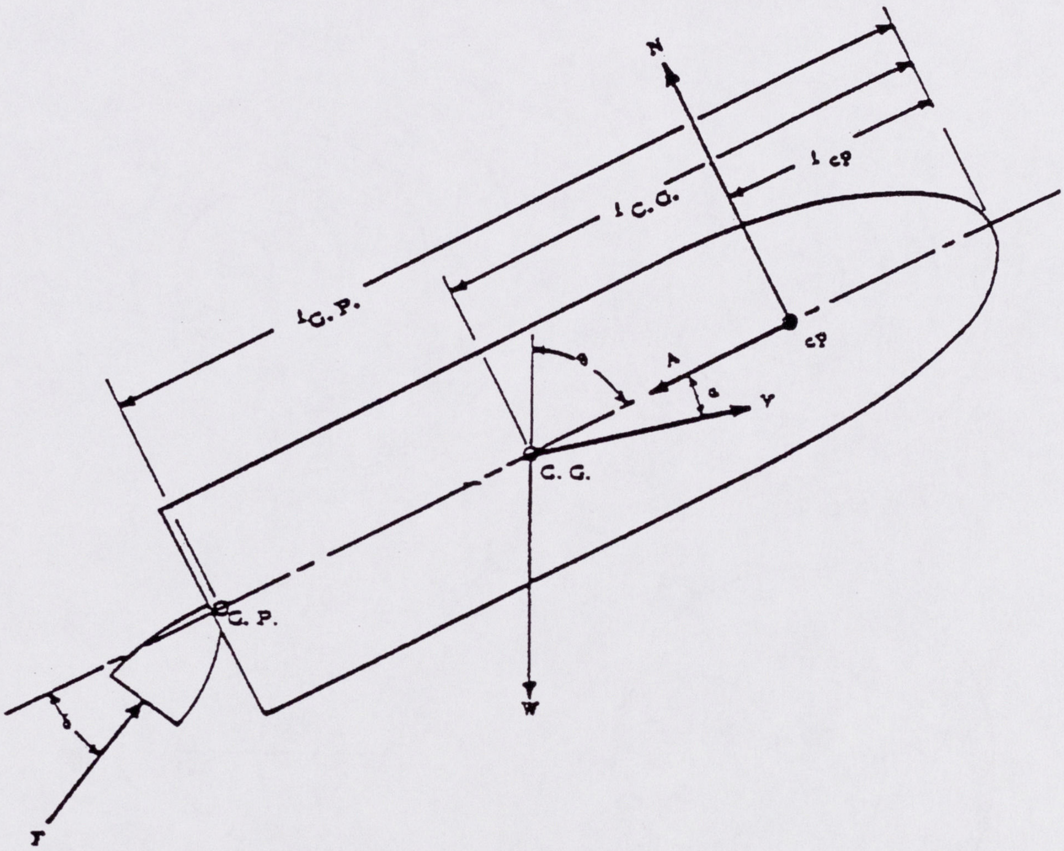


Figure 8a Aerodynamic Forces



G.P. = Gimbal Point
F = Thrust
δ = Monitor Deflection Angle

θ = Missile Attitude Angle
α = Missile Angle of Attack
N = Aerodynamic Normal Force
A = Aerodynamic Axial Force
W = Weight
V = Missile Velocity Vector

Figure 8b Balance of Forces on a Ballistic Missile

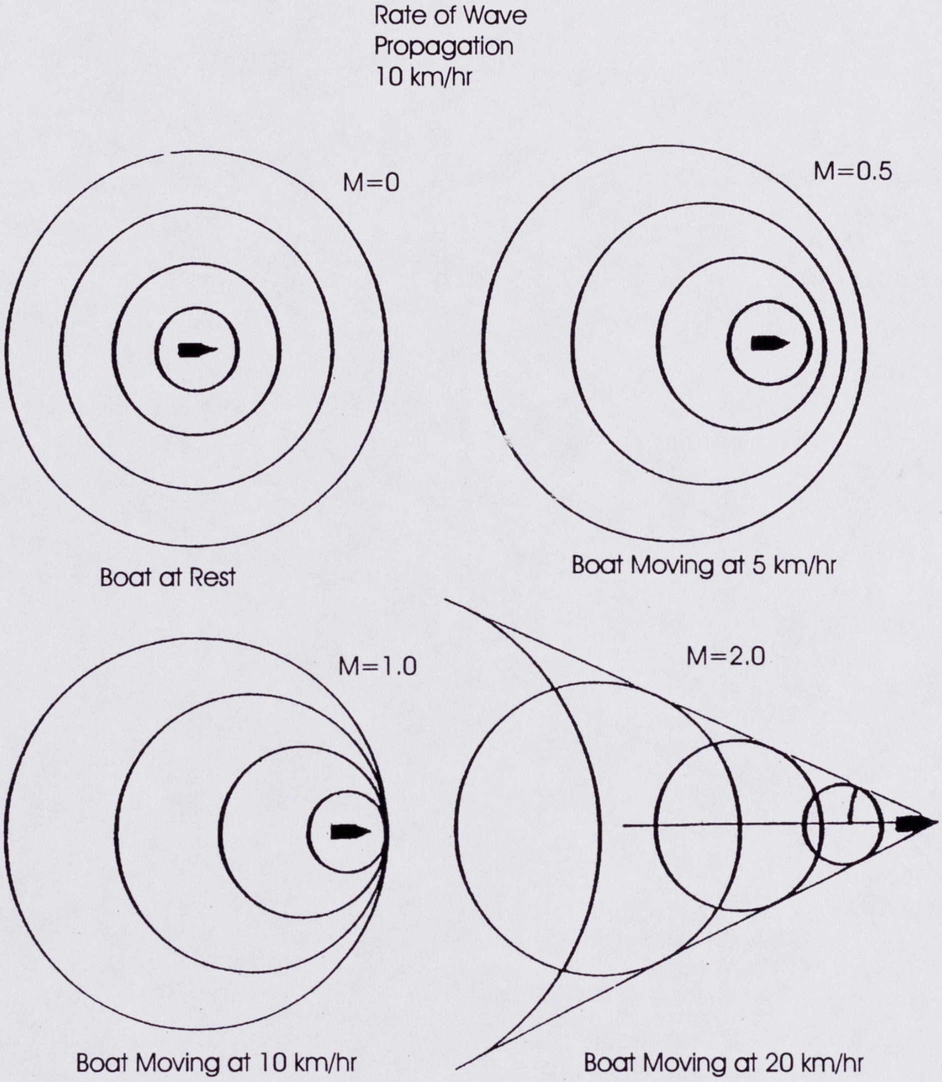


Figure 9 Analogy of Mach Numbers and Mach Angle

33. This final re-entry phase of flight is characterised by the missile (or more commonly a detached warhead or re-entry vehicle) experiencing great deceleration due to the atmospheric drag forces.

- Aerodynamics

34. Aerodynamic forces act on any object which is moving relative to air, and are typically important only for the earliest and latest phases of missile flight. They result from the impact of air molecules on the outer surfaces of a missile and cause 'drag', which leads to decelerations and deflections in its flight. Other consequences are heating and structural loading problems (Figure 8a).

35. After the missile is first launched, a pressure disturbance is created in front of it, travelling at the speed of sound. As the missile speed increases towards this value, a build up of pressure occurs near the nose tip, leading to a shock wave and increased resistance.

36. The forces are divided into pressure (or wave) drag, friction drag and base drag. Pressure drag acts normally onto the outer surface of the vehicle.

37. Friction drag results from shearing stresses set up in a viscous fluid when layers within it are moving at different speeds. These occur close to the surface of a body over which air is passing. The frictional force is determined by the extent to which the fluid flow is slowed down by the body.

38. Base drag is caused by suction effects acting on the moving body because of low air pressures created in its wake. It is turbulent eddies set up in the air flow behind bodies with flattish bases which lead to this phenomenon.

39. An important concept employed in the study of the aerodynamic effects is the centre of pressure, which is the point (on the missile or 'body') through which the resultant of all the aerodynamic forces passes. Studies of the effect on the location of this point for given body shapes under changing airflow conditions are fundamental to missile design.

40. If the centre of pressure of a missile is located forward of the centre of gravity the aerodynamic lift forces will tend to rotate it about the centre of gravity and increase the angle between the missile body and the direction of motion (often called the 'angle of attack'). Such a situation is unstable and some sort of attitude control system would be required to enable the missile to fly successfully. The arrangement of these forces on a missile is shown in Figure 8b.

41. There are four distinct flight regimes characterising the different possible aerodynamic environments experienced by a body moving through air (or in fact any 'fluid'). They each correspond to a particular type of air flow around the body, and are named according to the its speed, being called the subsonic, transonic, supersonic and hypersonic cases.

42. At properly subsonic speeds the body is travelling through the air slower than that of sound and therefore also less than that of the air disturbance or 'pressure wave' created. The air flowing past the body is also everywhere moving slower than this critical value. As the body speed is increased, a situation is reached, close to the speed of sound, where local supersonic flow regions are set up.

43. This condition of mixed flow characterises the transonic regime, and it persists as the body speed increases to that of sound, and slightly beyond. It is loosely defined as extending from 0.8 M to 1.2 M (where M is the local sound velocity).

44. Further increases in body speed result in a situation developing where the air flows are almost wholly faster than the speed of sound, with smooth flow over the surface. This is the 'supersonic' case. For bodies, or missiles, travelling at supersonic speeds, the air disturbance takes on a cone shape, characterised by the semi–vertex angle, the so–called 'Mach Angle'. The cone contains all the air disturbances produced by the body – they are not detectable up–stream. (see Figure 9).

45. At higher and higher supersonic speeds the preceding shock wave moves in closer to the body surface, and the trapped flow layer becomes very hot, sometimes causing dissociation, chemical reactions or even ionisation in the air.

46. When these result, usually at body speed greater than five times the local sound velocity (or 5 M), the flow regime is defined as being hypersonic. The actual speed at which these conditions are created depend on the shape of the body being flown.

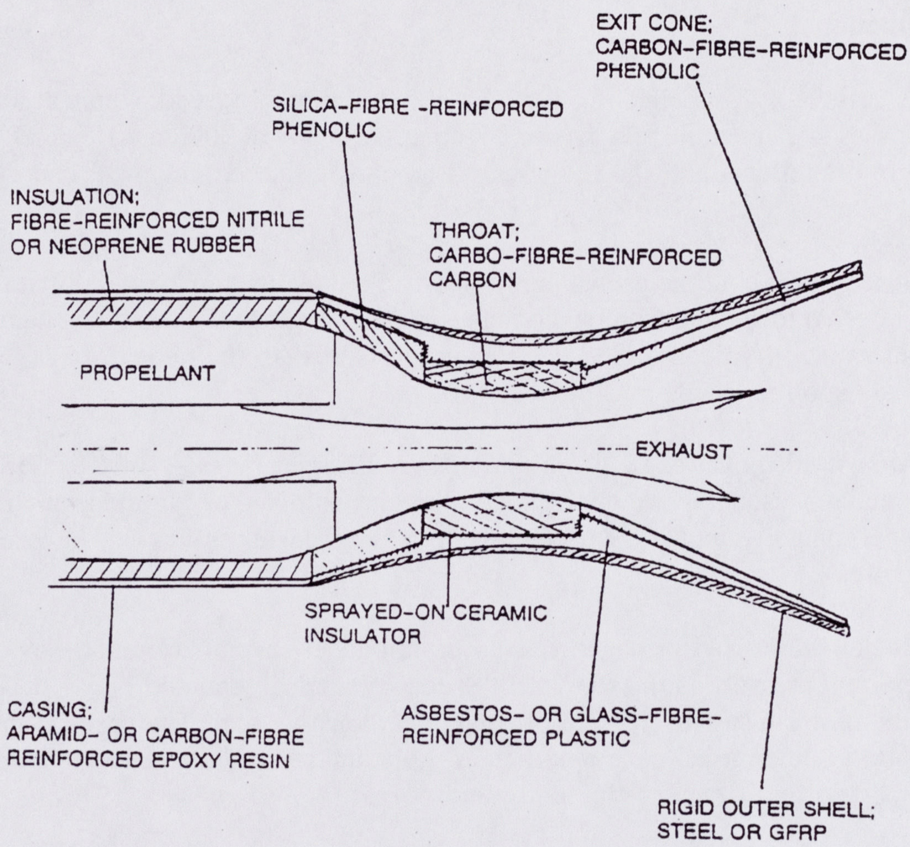


Figure 10 Section Through a Modern Solid Fuel Motor Nozzle constructed out of Typical Materials

ROCKET MOTOR TECHNOLOGY

- Introduction

47. A missile is propelled forward by the reaction produced when a stream of high velocity gases is ejected in the opposite direction (typically at 3000 m/s). The efflux is created by burning propellants and the net effect is to transfer stored chemical energy into kinetic energy.

48. Strictly speaking the propellants consist of a 'fuel' and an 'oxidant', but often they are together referred to as fuel. Combustion takes place in a specially designed chamber, and very high temperatures (typically 3000 deg.C) and pressures (in the range 2 to 15 MPa ie. 20 to 150 bar) are soon reached.

49. Almost all rocket engines are one of two different types - solid or liquid, according to the propellants used. Hybrid engines, burning one solid and one liquid propellant have been tested experimentally, but are extremely rare and, as far as is known, have not been used operationally.

50. Rocket motor performance can be described in several different ways. Perhaps the most important measure is the so-called 'Specific Impulse' (denoted Isp) - defined to be the ratio of the motor thrust to the rate of propellant consumption. The specific impulse of any given motor is determined by the particular propellants used, the proportions in which they are burned, and the design of the motor and nozzle.

51. The hot gases produced in the combustion chamber are channelled out of the motor via the nozzle, which is very carefully designed to maximise the resultant net thrust. The shape normally adopted is that of a convergent-divergent curve known by the name of De-Laval.

52. Nozzles normally consist of an external steel shell, with carbon phenolic and graphite throat inserts, and liners of carbon or silica phenolic tape in the expansion cone (Figure 10).

53. Typically the gases move subsonically as they are compressed and approach the narrowest section of the nozzle (known as the throat), reaching sonic velocity on passing through, and becoming supersonic on exiting.

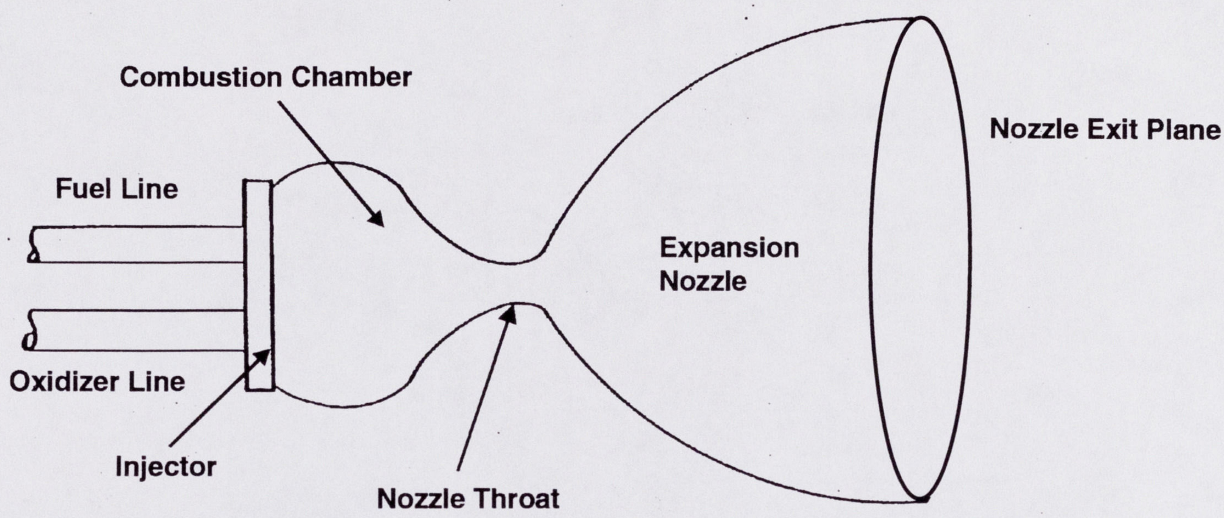


Figure 11 The Liquid Propellant Rocket Engine (schematic)

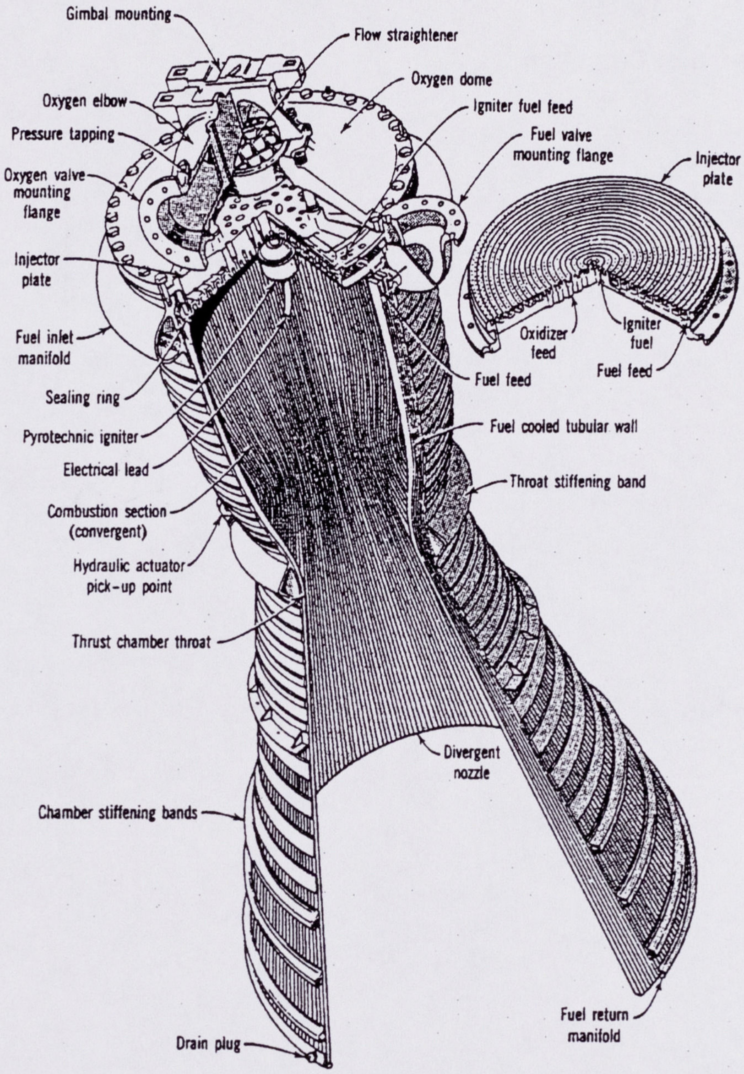


Figure 12a Thrust Chamber for a Liquid Engine

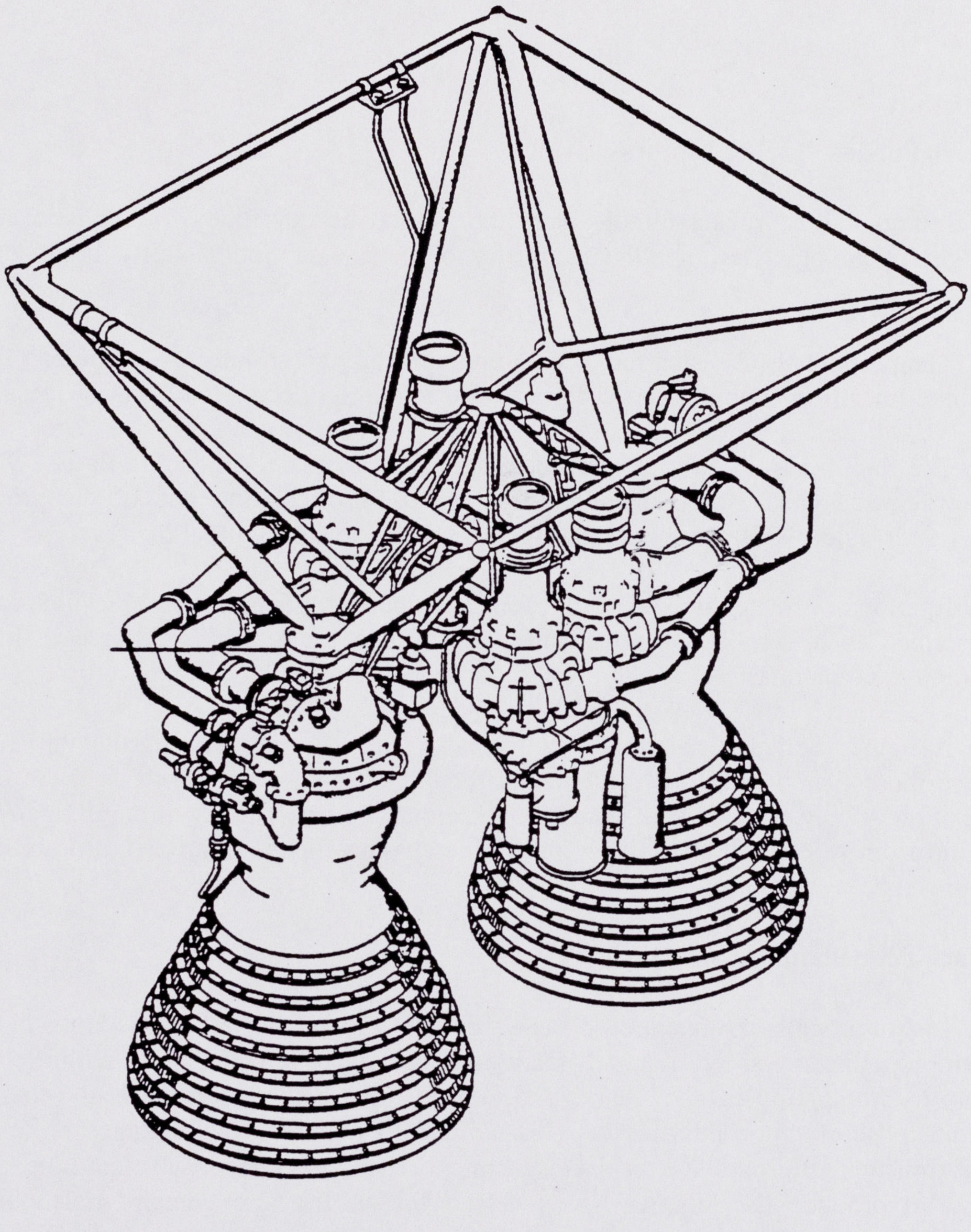


Figure 12b   Titan 2 First Stage Engine

- Liquid Fuelled Rocket Motors

54. Liquid fuelled rocket motors were the first to be developed for ballistic missiles. Although of complex design, the chemistry of their operation is fairly basic and well understood.

55. The propellants are each fed at high pressure through an injector, producing fine jets which intermix in the combustion chamber, where ignition occurs. See Figure 11.

56. The high pressure gases produced exit through a nozzle, producing thrust. Often the exit nozzles and combustion chambers are cooled by circulating one of the propellants through their outer walls. A typical arrangement is shown in Figure 12a.

57. Ignition of some combinations of propellants occurs spontaneously (in which case they are described as 'hypergolic'), in the other cases an electrical sparking device is fitted into the combustion chamber.

58. A liquid fuelled rocket motor suitable for use in a ballistic missile will typically consume more than 50 kg of propellant per second, so great care has to be taken over the design of the supply system. This would rely on either pressure forcing or pumping to transfer the liquid from storage tanks to the engines. The engines for the Titan 2 ICBM are depicted in Figure 12b.

- Liquid Propellants

59. Liquid propellants are classified as either monopropellants or bipropellants. In the case of monopropellants, a single liquid is made to decompose violently, often with the aid of a catalyst, to produce propulsive gases. They do not give high performance and their use is restricted to short range missiles or to individual low thrust missile stages or to attitude control thrusters. Bipropellants utilise a chemical reaction between two liquids ie. fuel and oxidant, to produce the required gases - and this is the arrangement most commonly encountered; the engine will normally be designed to operate with one particular fuel/oxidizer combination and mixture ratio.

60. The suitability of any fuel or fuel combination is assessed against a number of criteria for overall missile performance, including calorific value, optimum mixture ratio for maximum combustion efficiency, density, and handling and storage properties, and engine design requirements.

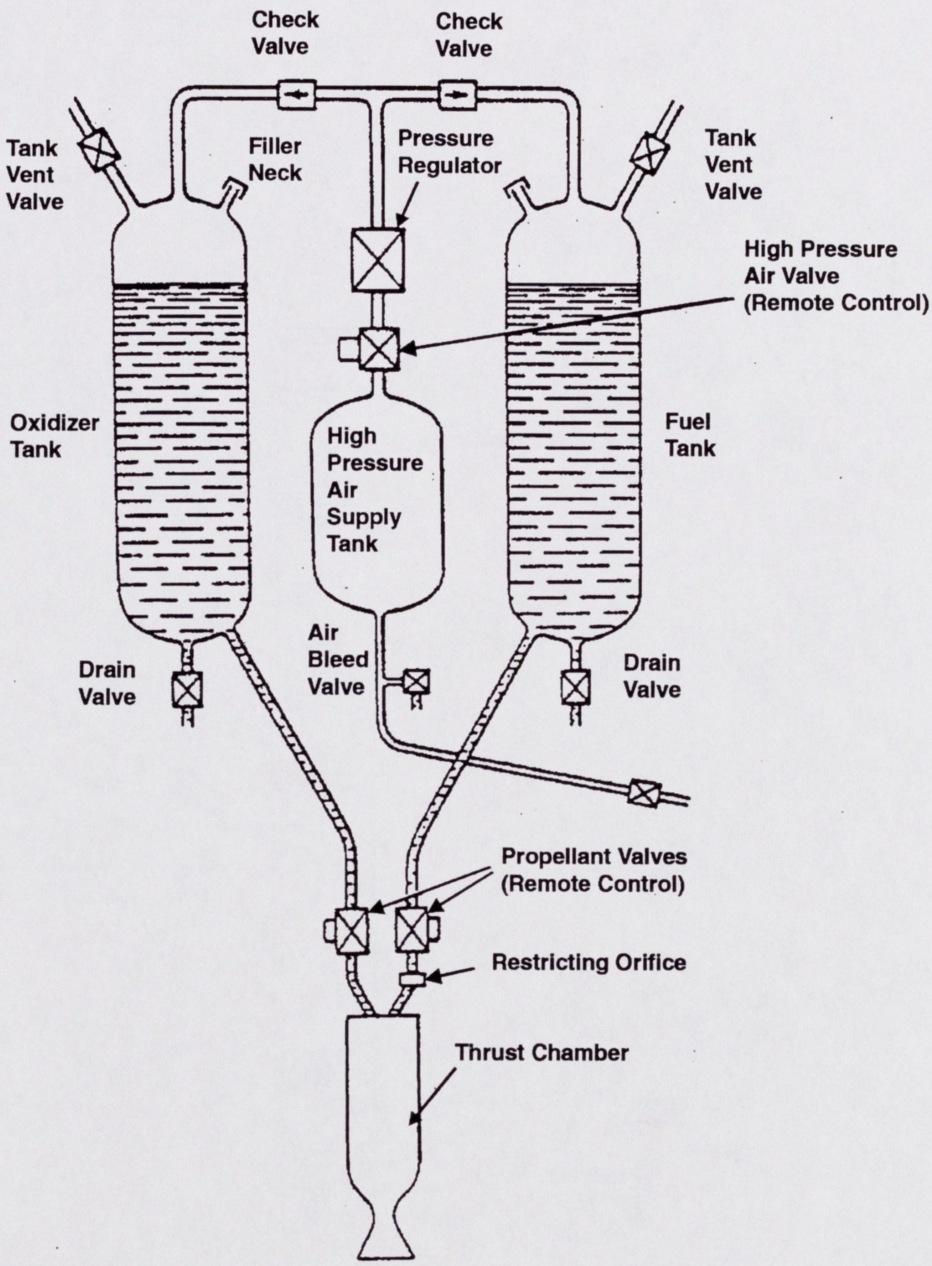


Figure 13 Schematic Diagram of a Liquid Propellant Rocket Engine with a Gas Pressure Feed System

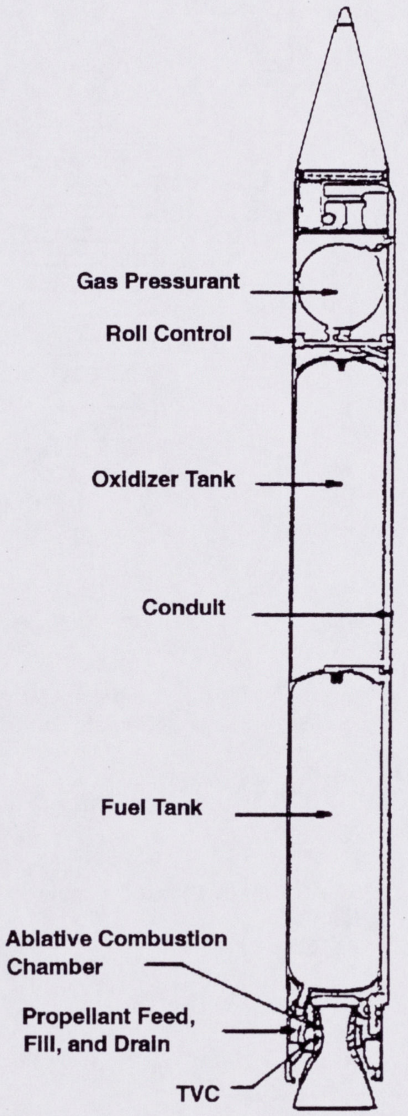


Figure 14 A Single-stage Missile with Pressure-fed Liquid Engine

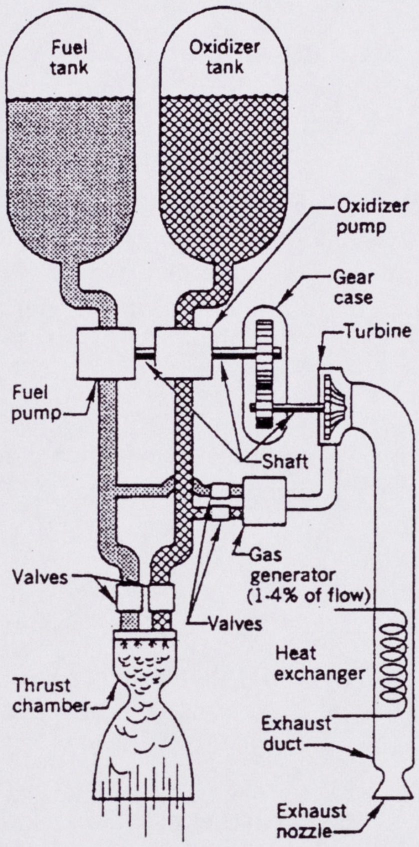


Figure 15   Schematic Diagram of a Liquid Propellant Rocket Engine with a Turbopump Feed System

61. The two propellants are stored in separate tanks within the missile, they are known (confusingly) as either fuels or more correctly as fuel and oxidant. They are routed by two sets of piping and valves to the combustion chamber, into which they are injected.

62. Many propellants are gaseous at room temperature and have to be cooled, liquified, and stored at very low temperatures (and are consequently termed cryogenic). They require very special handling to prevent evaporation, dangerous pressure build-ups and icing blockages, and cannot be stored in missile tanks for long periods. At one time commonly used for ballistic missiles, they have now been superseded by more manageable storable propellants.

63. Particularly stable and storable propellants which can be stored almost indefinitely in a missile's tanks are known as 'packageable'. Examples of these are given below.

<u>Oxidants</u>

64. Nitric acid is a common choice of oxidant. It is most widely used in the form of inhibited red fuming nitric acid (IRFNA) or just RFNA, in very highly concentrated form. Because of its corrosive properties, it requires special types of containing vessels, normally these are special stainless steels.

65. Dinitrogen Tetroxide is another frequently used oxidant, which can be stored almost indefinitely in sealed tanks. The main limitation with it is its relatively small operating temperature range, which renders it unsuitable for many mobile systems.

<u>Fuels</u>

66. Petroleum derivatives are widely used as missile fuels. Particularly suitable are kerosene and a specifically refined product designated RP-1. Both are mixtures of saturated and un-saturated hydrocarbons.

67. Hydrazine, and its derivatives are also frequently employed as fuels. Examples of these are monomethyl hydrazine (MMH) and unsymmetrical dimethylhydrazine (UDMH), both of which are classed as mixed hydrazine fuels (MHF). UDMH is the principal derivative fuel.

68. Mixed Amine Fuels consist of a mixture of UDMH and diethylenetriamine (DETA).

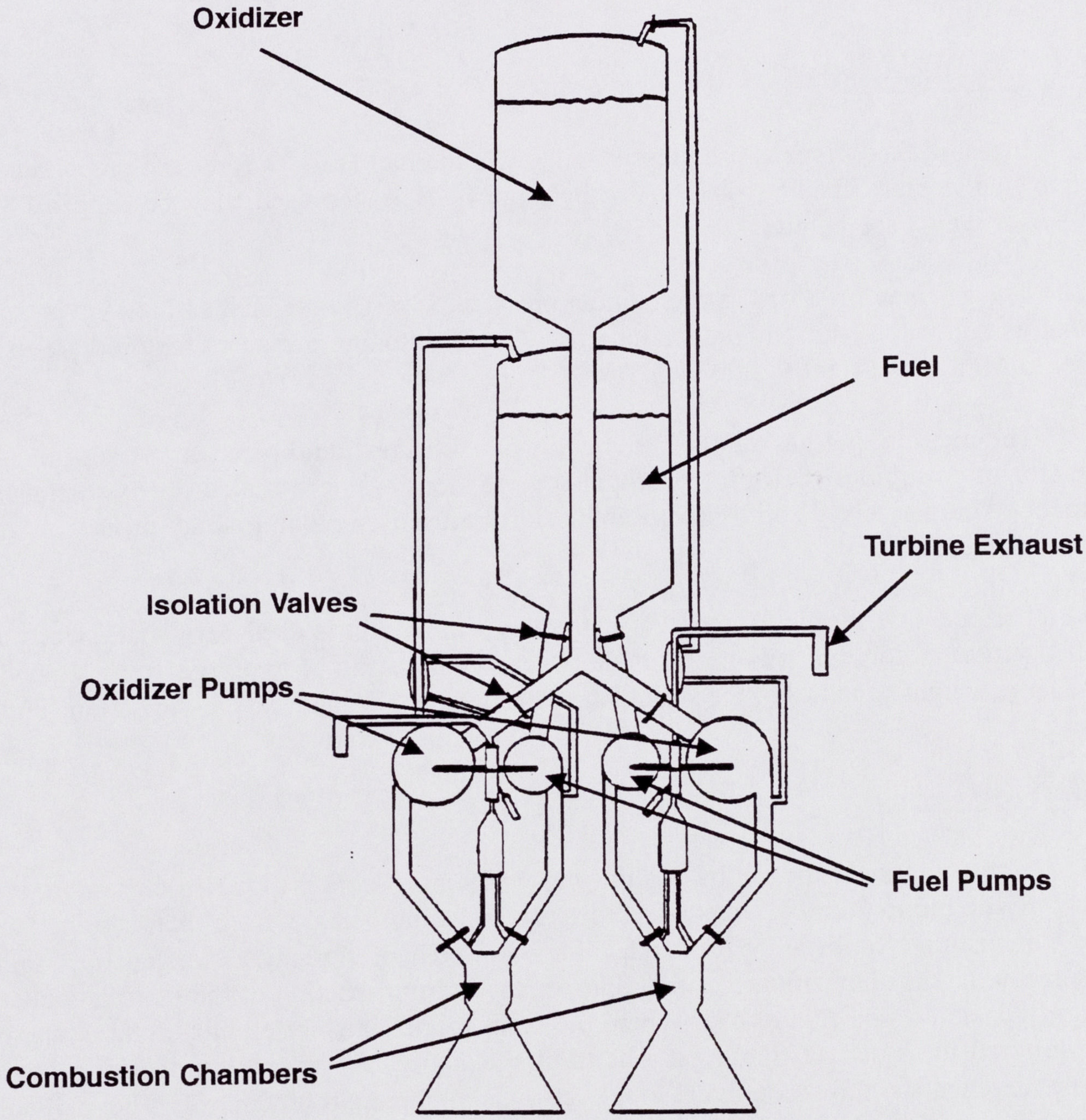


Figure 16 Schematic Diagram of the Titan 2 Missile First Stage

Pressure Feed Systems

69. Pressure feed systems use pressurised gas in the fuel tanks to force the propellant out and down the pipes feeding directly to the engines. The gas used may be supplied in a number of ways (see below).

70. The gas may be stored as such, under pressure, in a separate tank and fed via pressure regulators and valves into the propellant tanks. Typical storage pressures required are in the 20 to 30 MPa range (200 to 300 bar).

71. The pressurizing gas can be generated from solid or liquid reactants. A separate gas generator often mimics the primary propulsion reactions, using a scaled down combustion chamber. Alternatively a solid–driven unit could be used employing solid–propellant type charges (Figure 13).

72. The pressure–forcing method is extremely simple and is used very successfully for smaller rocket motors but it is not suitable for the main stages of the larger vehicles owing to the large weight penalties of the strong tanks needed to withstand the pressurisation (Figure 14).

Pump Feed Systems

73. Pump feed systems are by far the most common seen in liquid rocket motors. A turbine driven pump ('turbo–pump') is used to move the propellants from their storage tanks to the combustion chamber. The turbine itself is powered by a 'working' fluid, generated under pressure by the decomposition of a monopropellant or from reaction of the main propellants in a gas generator (see Figure 15). Where the main propellants are employed the system is often referred to as a 'bootstrap' type. The turbine exhaust may be fed into the main engine exhaust to enhance thrust or even to effect a small amount of control. The particular arrangement for the Titan 2 ICBM fuel supply (for two main engines) is shown in Figure 16.

– Performance

74. The performance of different liquid propellant combinations is shown in Figure 17. Real case values for the Titan 2 are given in Figure 18.

OXIDANT	FUEL	SPECIFIC IMPULSE N SEC/kg	VOLUME MIXTURE RATIO OXID/FUEL
Chlorine Trifluoride	Hydrazine	2883	1.53
	UDMH	2746	1.31
	RP1	2530	1.42
	MHF 1/1	2815	1.42
Nitrogen Tetroxide	Hydrazine	2863	0.93
	UDMH	2795	1.42
	RP1	2707	2.26
	MHF 1/1	2824	1.24
	HYDYNE	2766	1.61
Nitric Acid 15%	Hydrazine	2775	0.95
	UDMH	2706	1.51
	RP1	2628	2.48
	MHF 1/1	2736	1.26
	HYDYNE	2677	1.70
Hydrogen Peroxide 95%	Hydrazine	2766	1.54
	UDMH	27.26	2.53
	RP1	2677	4.18

Figure 17 Liquid Propellant Performance

	SEA LEVEL	ALTITUDE (76.2 km)
THRUST	1.9×10^6 N (430,000 lbs)	2.1×10^6 N (474,000 lbs)
SPECIFIC IMPULSE	256.5 sec	287.0 sec
CHAMBER PRESSURE	5.402 MPa (783.5 psia)	5.402 MPa (783.5 psia)
OXIDIZER (NITROGEN TETROXIDE) FLOW RATE	492.9 Kg/sec (1086.6 lbs/sec)	492.9 Kg/sec (1086.6 lbs/sec)
FUEL (50% HYDRAZINE, 50% 50% UDMH) FLOW RATE	246.5 Kg/sec (543.4 lbs/sec)	246.5 Kg/sec (543.4 lbs/sec)
BURN DURATION	165 seconds	
WEIGHT (OVERALL-BOTH ENGINES)	DRY 940 Kg (2072.5 lbs)	
PROPELLANT IGNITION	HYPERGOLIC	

Figure 18 Characteristics of the Titan 2 Engine

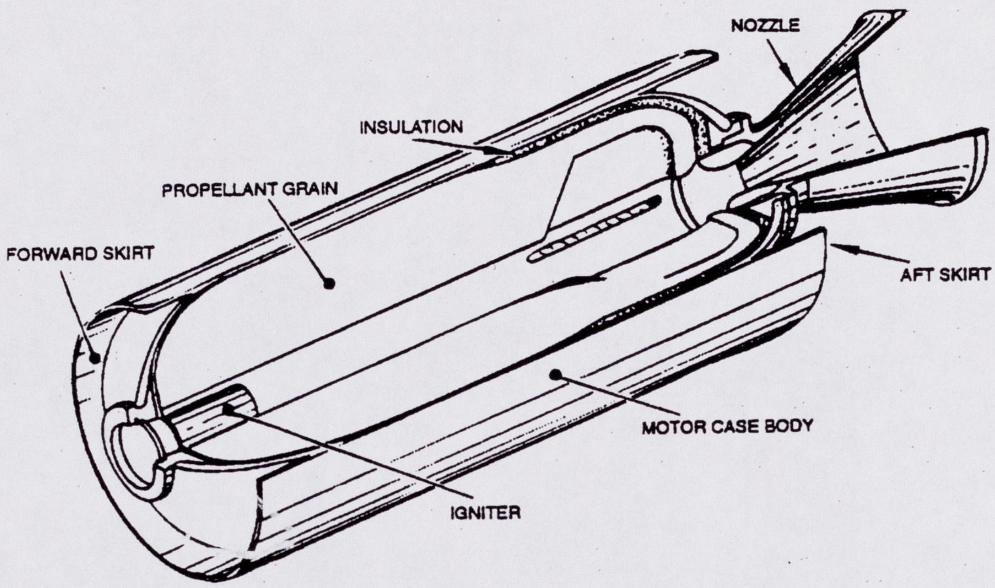


Figure 19 A Typical Solid Rocket Motor

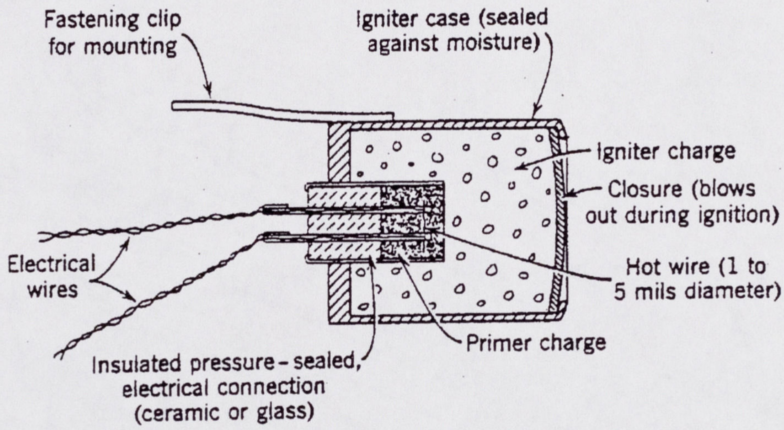


Figure 20a Schematic Diagram of an Igniter

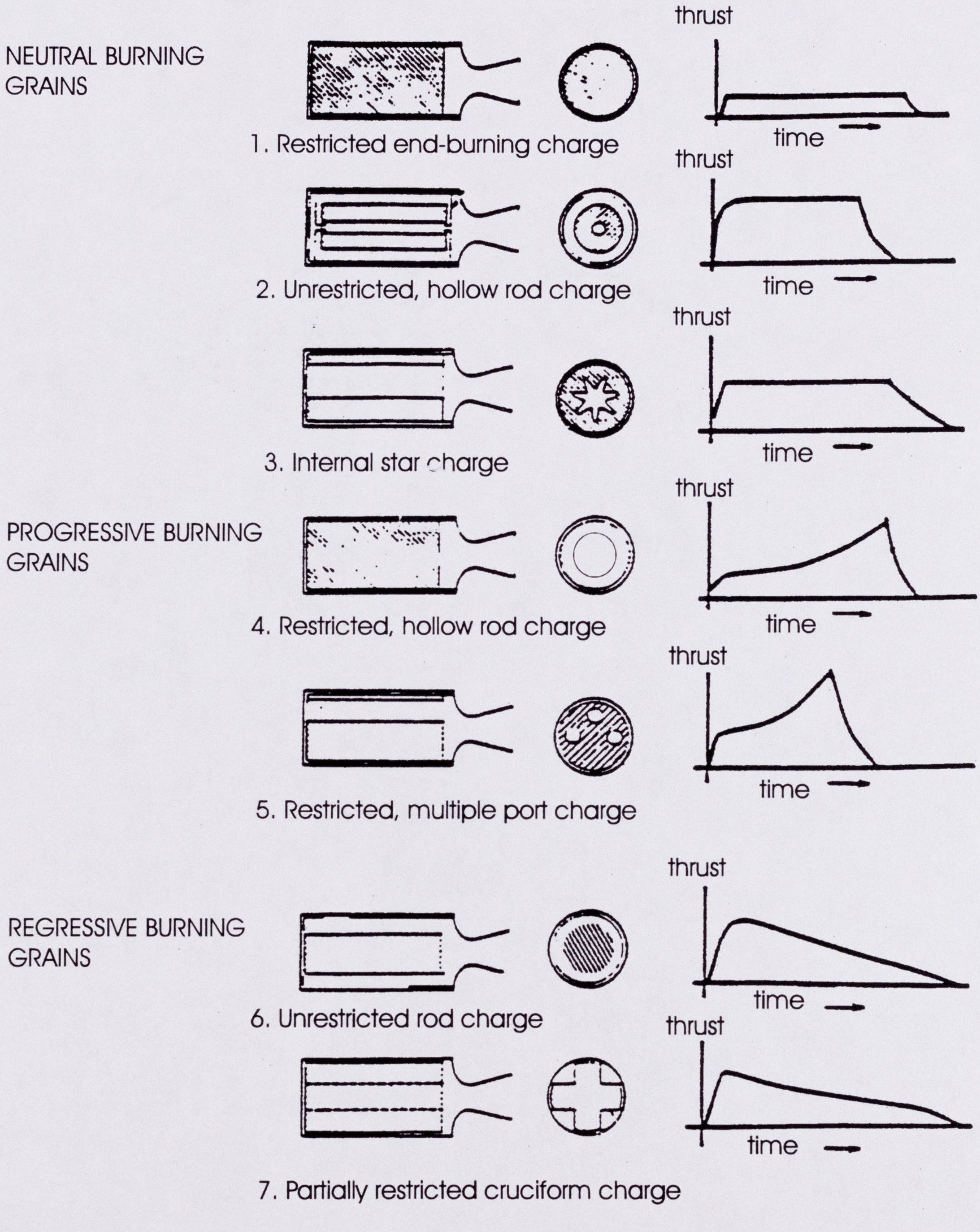


Figure 20b Typical Grain Configurations and Thrust Profiles

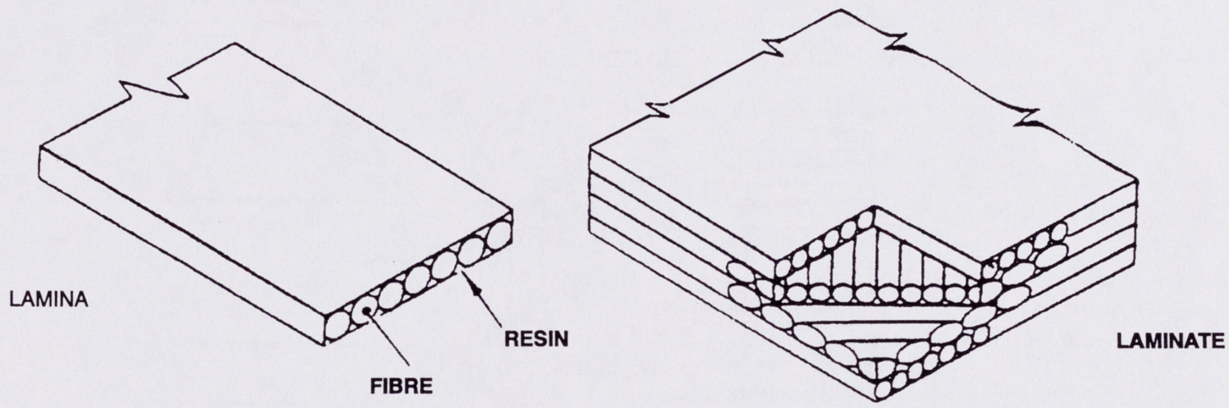


Figure 21a Laminate Composite Construction

	D6aC Steel	Maraging Steel	Titanium (6% Al – 4%V)	Glass Filament Composite	Organic Filament Composite
Tensile Strength (MPa)	1586	1724	965	1172	1724
Density (kg/m^3)	7833	7999	4623	1993	1384
Strength/Density	0.20 x 10^6	0.22 x 10^6	0.21 x 10^6	0.59 x 10^6	1.25 x 10^6
Modulus (MPa)	0.20 x 10^6	0.19 x 10^6	0.11 x 10^6	0.03 x 10^6	0.08 x 10^6

Figure 21b Comparison of Solid Motor Case Materials

– Solid Fuelled Rocket Motors

75. Solid fuelled rocket motors are very simple in design – essentially a casing filled with a solid propellant charge and attached to an exit nozzle (see Figure 19). The charge contains a mixture of fuel and oxidant, and is initiated by the use of an electrically fired igniter (Figure 20a).

76. The casing must withstand the high temperatures and pressures of the gases produced by the burning propellant, and has to be well lined with insulating and inhibiting layers, which does result in a weight penalty. Typical gas conditions produced are:– pressure in the range 3.4 to 24 MPa and temperatures of from 2500 to 3500 deg C.

77. Motor performance depends very strongly on the way the charge is arranged within the chamber. Usually some sort of longitudinal layout is adopted, with a cross–section design such as those shown in Figure 20b. Other factors which are also important are the propellant density and burning rate, and these are all assessed during motor design.

78. One of the most popular charge configurations is the 'star' (see Figure 20b). This is suitable when high thrusts and low burning times are required. Careful design is necessary though to ensure that burning does not stop when the outer edges of the charge are reached, at low chamber pressures, thus incurring a penalty of high unburnt mass remaining, and performance drop–off.

79. Weight considerations, important to the overall missile design, often lead to the cases being made out of structural composites (laminates of high strength fibrous materials such as fibreglass, kevlar, or graphite held in an epoxy resin matrix), they are both light and strong in tension, Figure 21a. Alternatively high–strength steels or titanium alloys can be selected. The properties of these materials are shown in Figure 21b.

– Solid Propellants

80. The propellants used fall into one of two categories – double–base or composite. The former contain fuel and oxidant components bound together at the molecular level, and are normally a mixture of nitrocellulose and nitroglycerine. The latter are a mixture of many ingredients, comprising fuel, oxidant, binder, curing agent, plasticizer and burn–rate catalyst.

TYPE	SPECIFIC IMPULSE N sec/kg
Extruded Double Base	2150 - 2250
Cast Double Base	2150 - 2250
Hydroxy-Terminated Polybutadeine	2550 - 2600

[Calculated for a chamber pressure of 6.89 MN/sq m and exit pressure of 0.1 MN/sq m]

Figure 22 Solid Propellant Performance

81. Double–base propellants (also sometimes called colloidal) are produced by one of two methods, either extruded – extruded double base (EDB) or cast – cast double base (CDB). A modified form, which contains added oxidant and explosive, is termed composite modified double base (CMDB).

– Performance

82 Details of the performance of solid propellants are given in Figure 22.

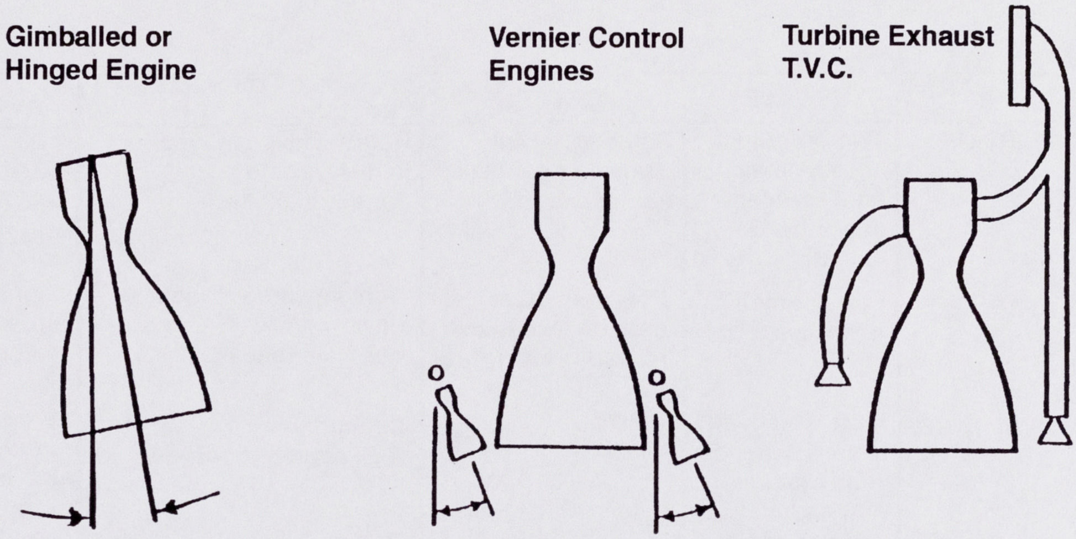


Figure 23 Thrust Vector Control Systems for Liquid Rocket Engines

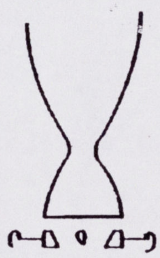
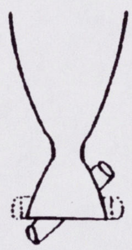
	JET VANES	JETEVATOR	HINGED OR GIMBALLED NOZZLE	GAS INJECTION
DESCRIPTION	Two or four aerodynamic heat resistant vanes inside exhaust stream	Rotating, airfoil shaped collar near nozzle exit	Rotary universal type joint at nozzle (hinge or gimbal)	Liquid or gas injection on one side of nozzle
MERITS	Can get high sideways forces	Low drag losses - erosion less than jet vane - low torque	Very low drag losses linear control characteristics	Light weight nozzle - rapid response
DISADVANTAGES	High drag even at zero deflection vane erosion non-linear variable shaft torque	Heavy	Difficult to seal, high actuation torques	Large side forces require excessive amount of secondary fluid complex system
				

Figure 24 Thrust Vector Control Systems for Solid Rocket Motors

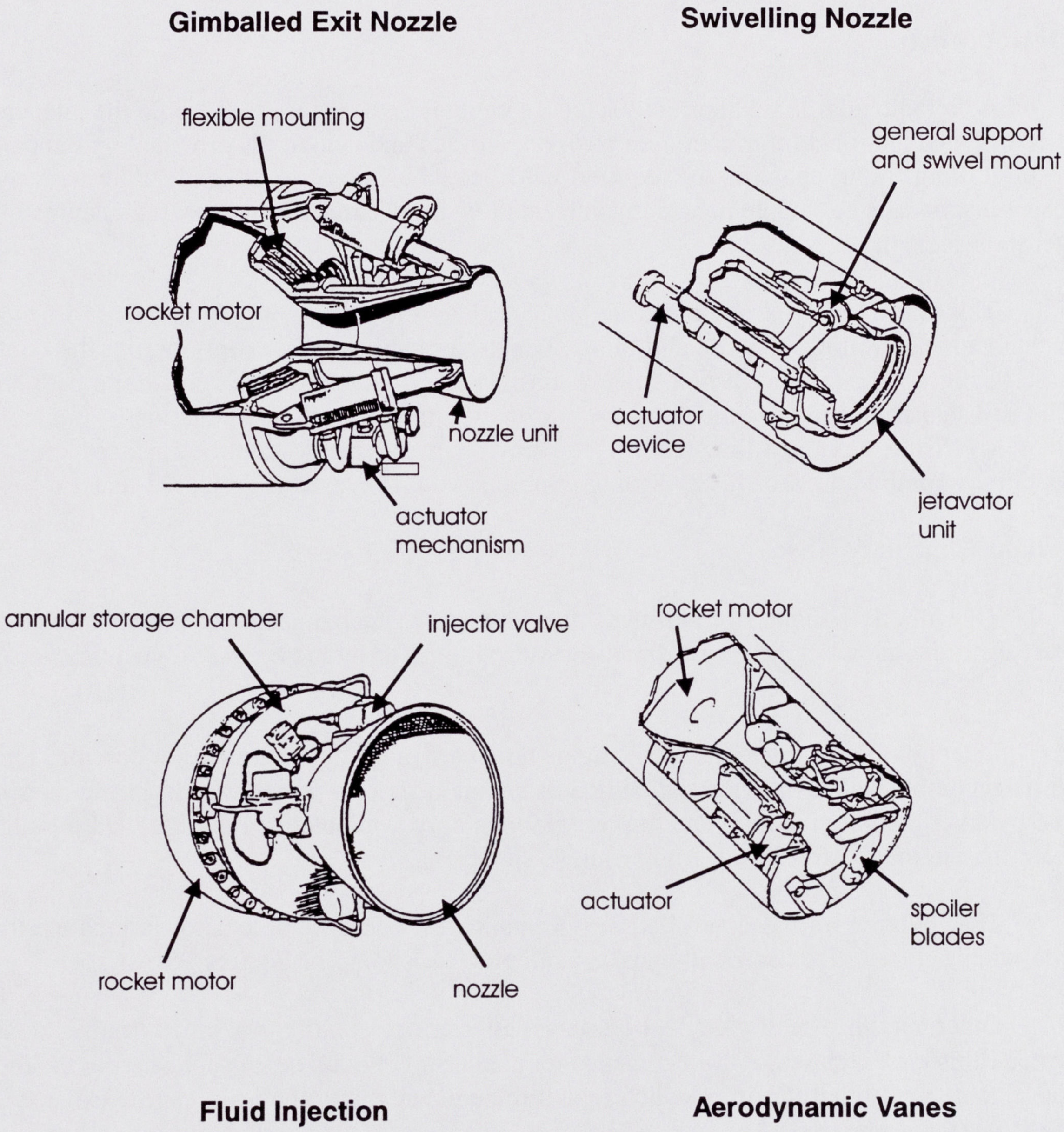


Figure 25 Details of Thrust Vector Control Systems

NAVIGATION, GUIDANCE AND CONTROL TECHNOLOGY

– Introduction

83. A ballistic missile will normally have a computer on board to steer it onto the intended trajectory. Navigational information on position, attitude and velocity is provided by onboard sensors during flight, enabling the required guidance adjustments to be made. Alternatively, these sensors can be supplemented by information from external sources (eg. navigation satellite systems).

84. This information is processed and analysed by the computer and signals fed to the mechanisms controlling attitude and thrust, which in practice operate only during the boost phase of flight, when there are numerous disturbing forces acting on the vehicle. Its path has to be adjusted from time to time either by altering the thrust level or orientation of the main motor, by firing auxiliary thrusters, or by moving aerodynamic control surfaces ('fins'). Sometimes combinations of these different options would be used (Figures 23 and 24).

– Flight Control Methods

85. The missile's flight is controlled after launch by changing the direction or level of thrust from the main engine, firing small thruster motors, or by moving aerodynamic control surfaces.

86. Directional changes to the main engine thrust are made by 'thrust vector control'. This can be accomplished by moving the engine or engine nozzle to point away from the missile axis (by a very slight amount). The former option is only available for liquid fuelled missiles where the engine is a relatively small unit.

87. The pivoting unit is controlled by mechanical links from an actuator (which exert a force when fed with an electrical signal). Examples are shown in Figures 25.

88. Other methods restricted to liquid fuelled engines are the use of additional small pivoted thrusters ('vernier control engines') mounted near the main nozzle and sharing the fuel supply, and small fixed thrusters which feed turbine exhaust into the main engine exhaust to deflect it. (See Figure 23).

89. Changes to the direction of thrust can also be made by moving tabs or vanes inserted into the exhaust (see Figure 24).

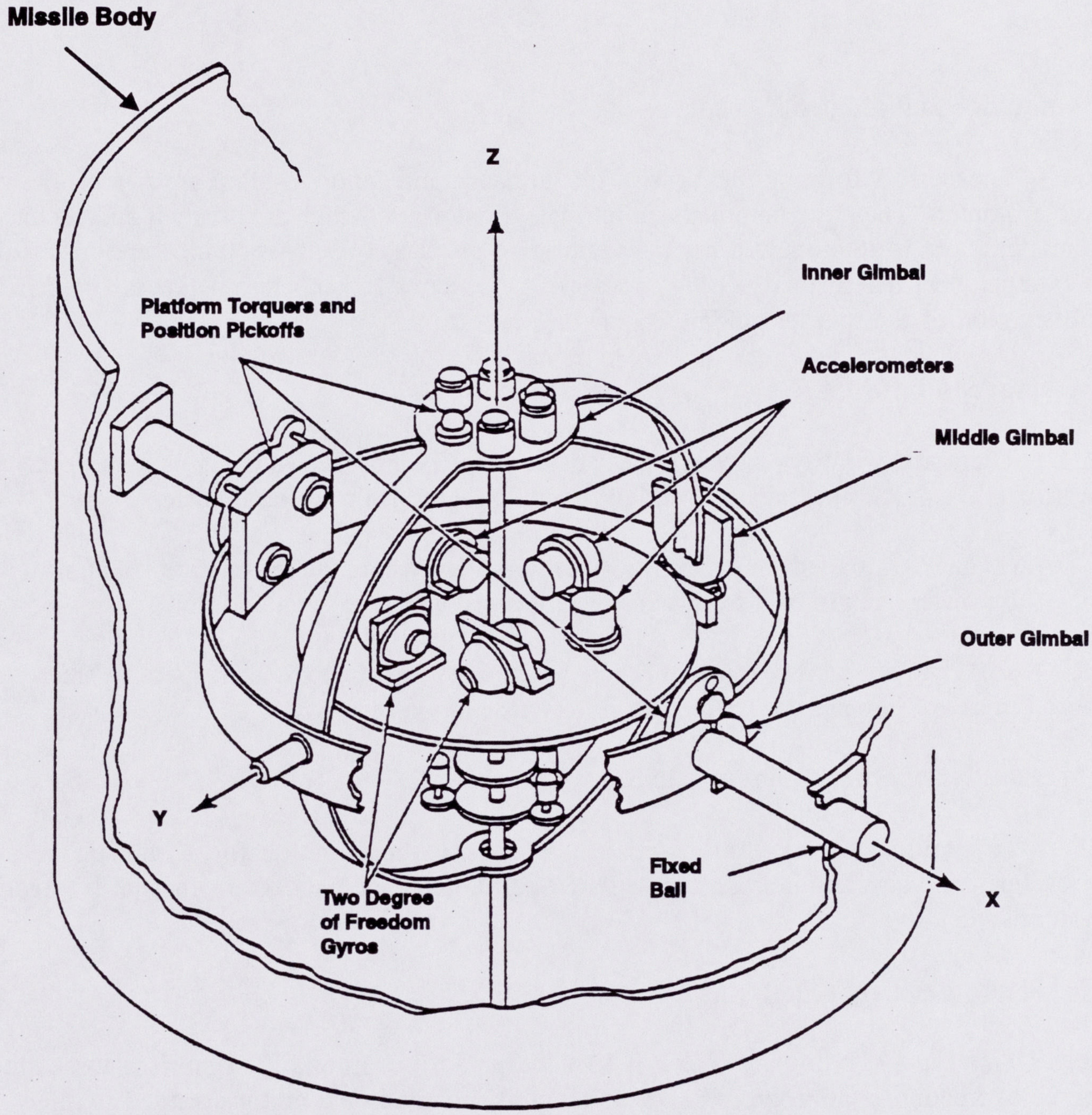


Figure 26a Inertial Platform

– Guidance and Control Sensors

90. The sensors forming the basis of the guidance and control system are gyroscopes and accelerometers. These are complex and intricate instruments which are difficult and expensive to manufacture to the required accuracy, but they are largely self–contained and insensitive to external electrical disturbance. A number of gyroscopes and accelerometers are used in the construction of the missile guidance unit (or 'platform').

– Guidance Platforms

91. There are two ways in which the sensors (usually mounted together as a platform) can be utilized to guide a missile, depending on their relationship to the missile structure.

(i) The "gimballed" or "stabilized" configuration where the sensors are isolated by means of gimbals from vehicle motion (see Figures 26a and 26b).

(ii) The "strapdown" configuration has the sensors fixed with respect to the missile, they are constrained to follow its motion.

– Inertial Navigation Systems – INS

92. To provide the necessary guidance and control information for a ballistic missile, gyroscopes and accelerometers are integrated into a guidance package or Inertial Navigation System (INS).

Gimballed (Stabilized) Platforms

93. This type of platform, which is in widespread use, normally comprises three single degree of freedom gyroscopes and accelerometers mounted on a unit suspended in three sets of gimbals, each with motor control .

94. As the missile moves, angular displacements occur between the platform and the missile axes. These are sensed by readout devices at the gimbals and feed the gimbal motors via servo loops to return the platform to its initial orientation.

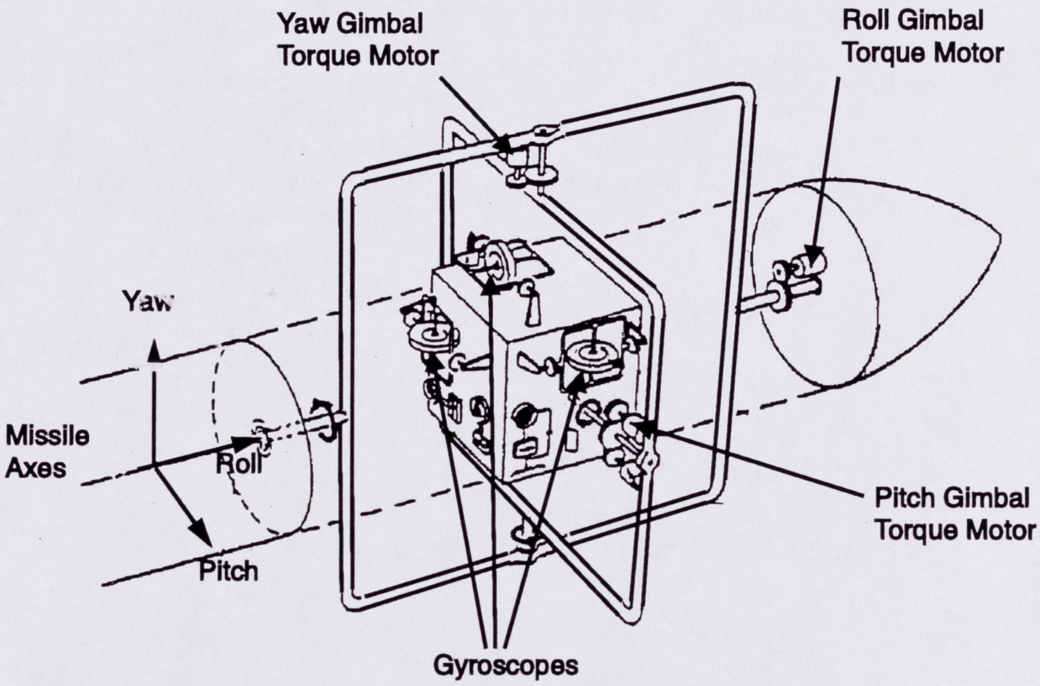


Figure 26b Missile Stabilized Platform

	GIMBALLED PLATFORM	STRAP-DOWN PLATFORM
Advantages	**Very Accurate**	**Mechanically Simple**
	Mechanical Isolation	**High Reliability**
		Robustness
		Cheap
		Ease of Repair
	Mature Western technology	**Ease of manufacture**
Disadvantages	**Expensive**	**Lower accuracy**
	Mechanically complex	**High gyro dynamic range**
	Lower reliability	**Complex (?) programming**
	Difficult to repair	**Relatively high computer load**
		Bandwidth requirements due to lack of isolation

Figure 27 Comparison of Platform Types

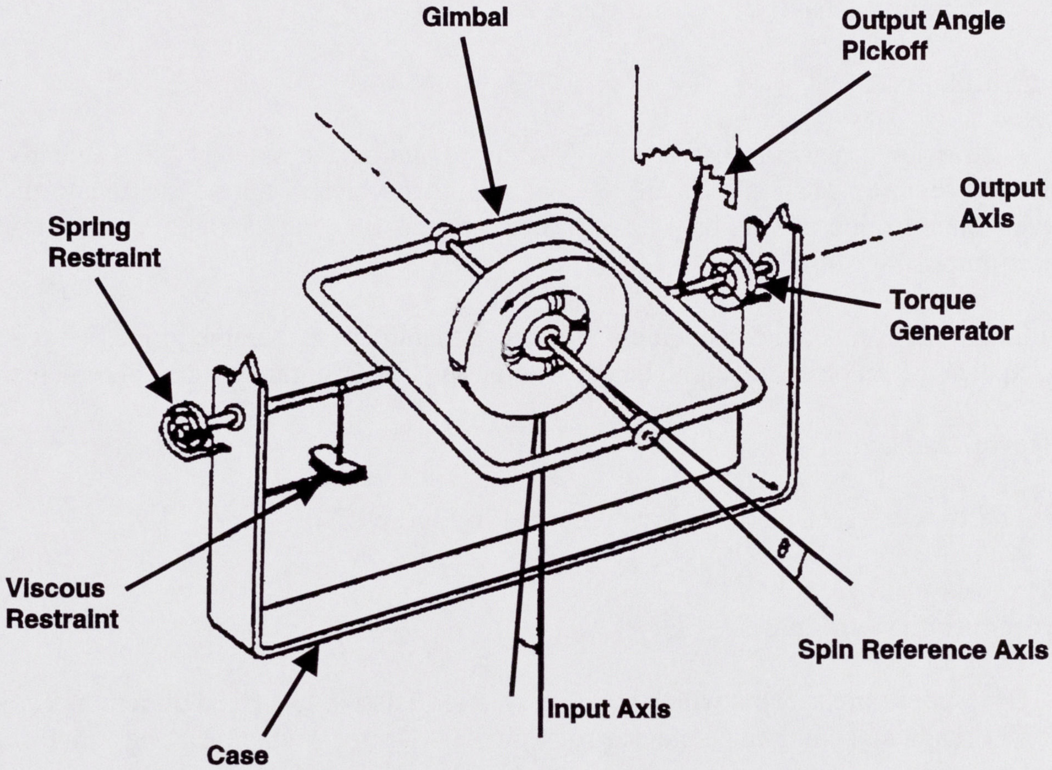


Figure 28 Operation of a Single Degree of Freedom Gyroscope

95. The gyroscope and accelerometer outputs are used by an on–board computer to calculate the required navigational information.

Strapdown Platform

96. A strapdown platform has all the gyroscopes and accelerometers fixed directly onto the missile structure . Their signals are fed to a computer which performs the transformations to convert them from a missile based axis system to an earth centred frame, and the required guidance outputs are obtained.

97. These platforms are considerably simpler to manufacture than the gimballed type, but at the expense of much more sophisticated computing and programming requirements.

– Platform Comparison

98. The two types of platform are compared in Figure 27.

– Gyroscopes (Traditional)

99. Gyroscopes are sensors which measure rotation relative to a fixed direction. Typically they are mechanical, containing a quickly rotating mass ("rotor") which, having a high angular momentum, tends to maintain a fixed direction. The attitude and angular motions of any structure in which it is fitted can be measured with respect to this direction.

100. Gyroscopes are produced with different arrangements of supporting gimbals, which restrict their freedom of movement to a greater or lesser extent. This leads to their being described as having one or two "degrees of freedom".

101. The gyroscope rotor is mounted via two shaft bearings, in a "gimbal" – a frame with bearing pivots. An arrangement such as this, mounted in a missile structure, would allow the gyro axis to turn about one set of axes, and is described as having one degree of freedom (Figures 28 and 29).

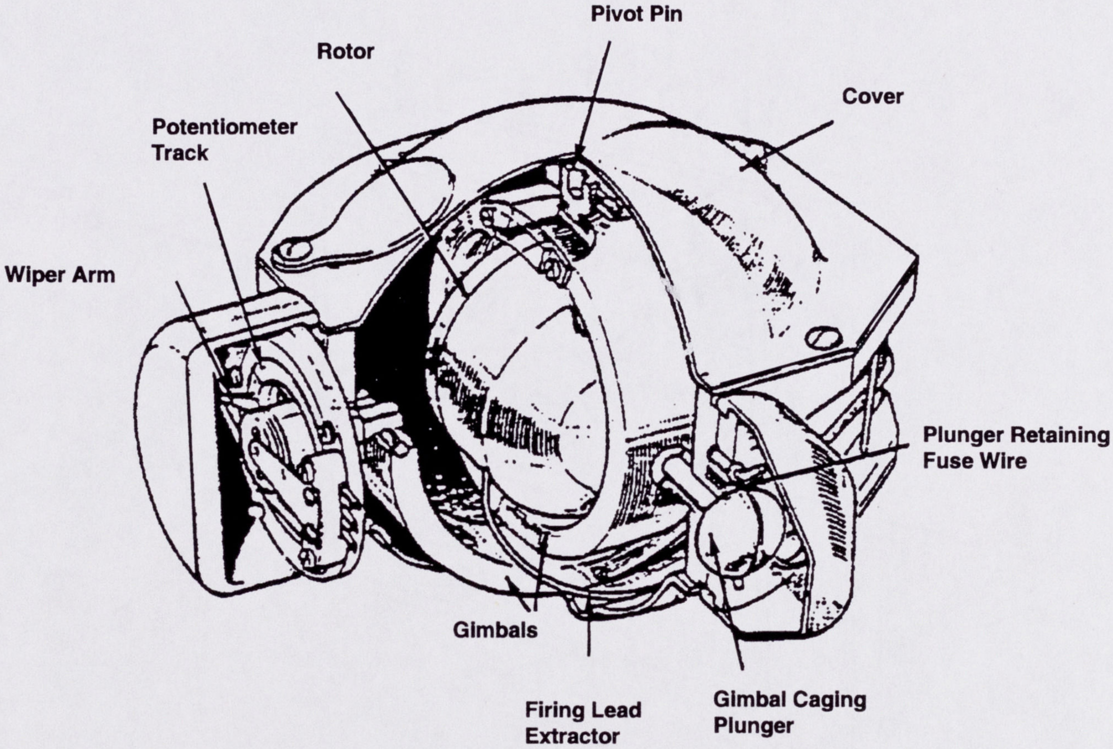


Figure 29 A Single Degree of Freedom Gyroscope

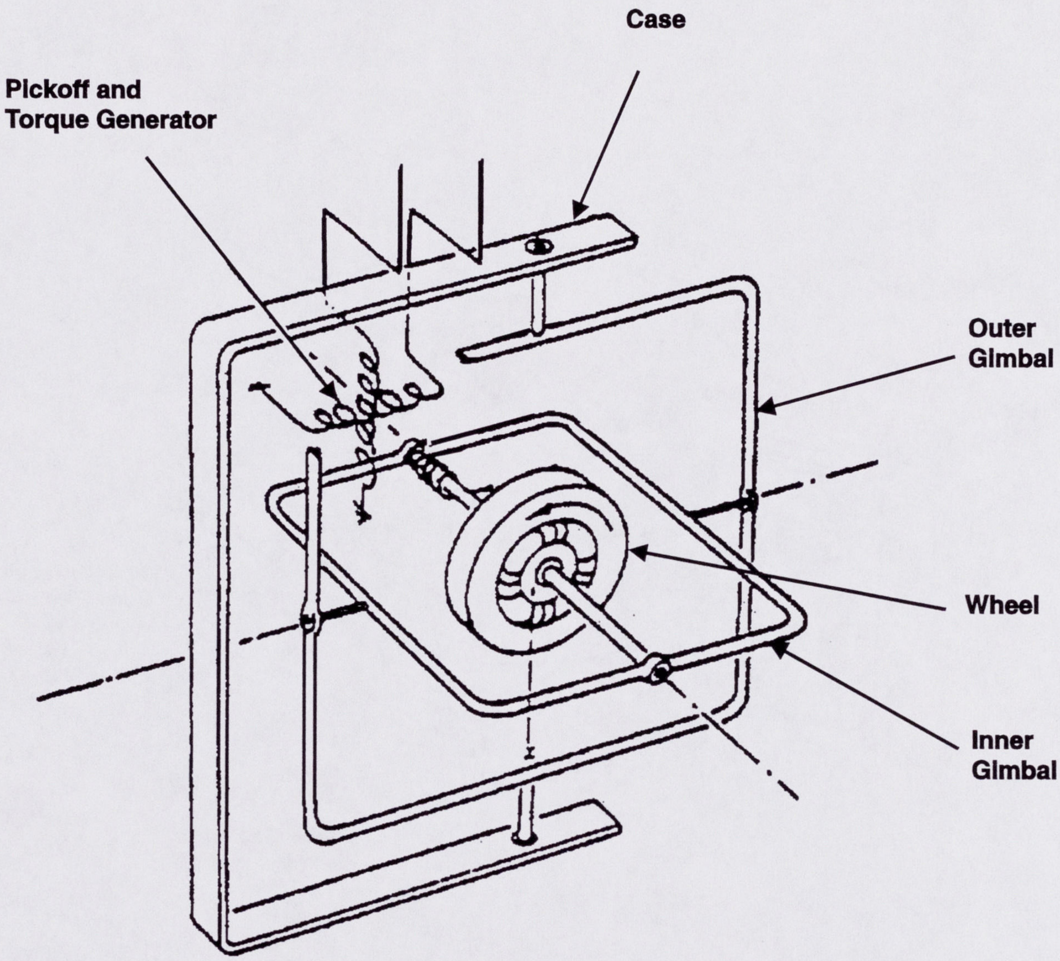


Figure 30 Two Degree of Freedom Gyroscope

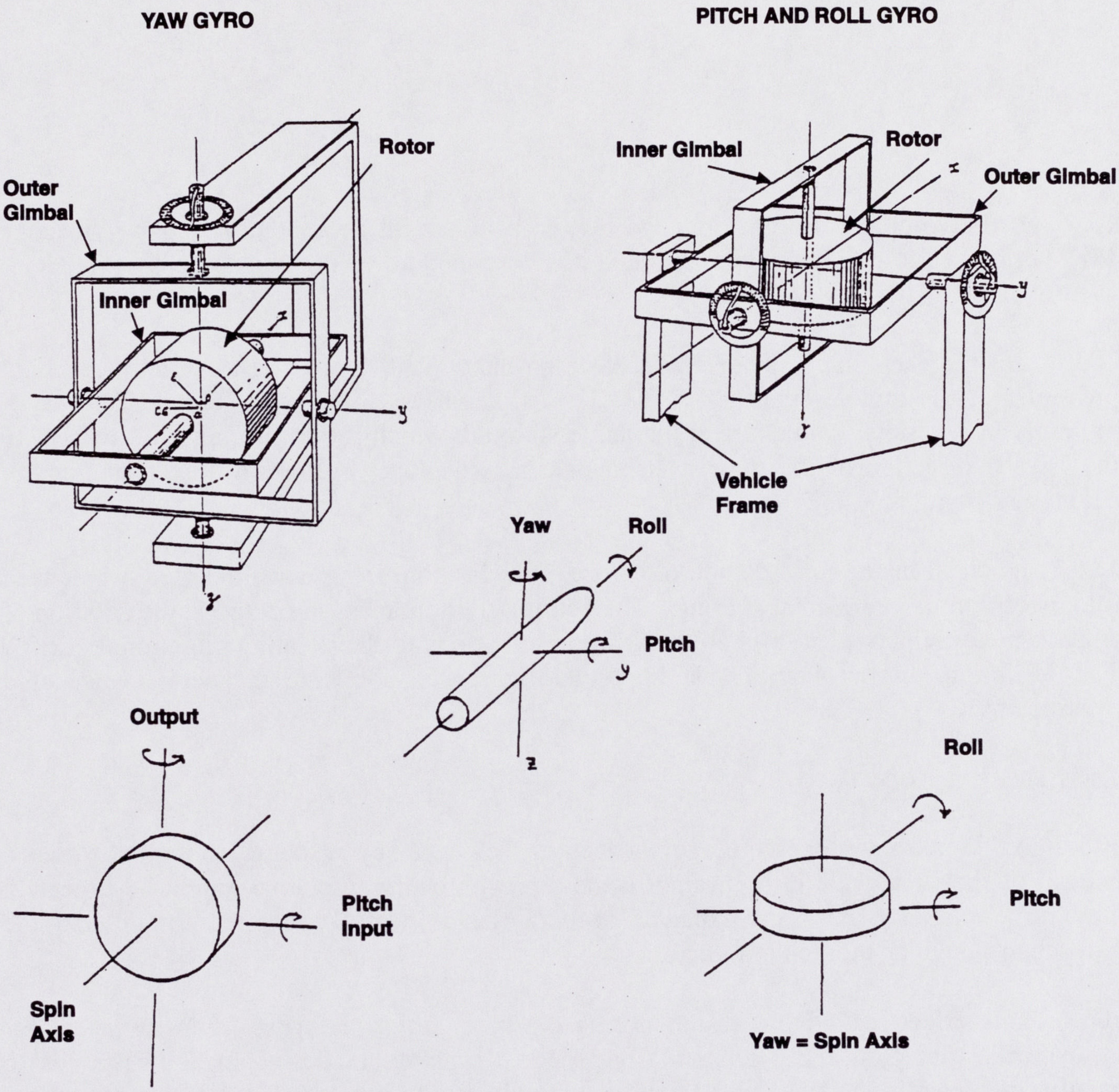


Figure 31 Free or Position Gyroscope

102. If this gimbal is in turn mounted by two bearings inside another one, the gyroscope axis will be free to turn about two axes and it is described as having two degrees of freedom. (See Figure 30).

103. A simple angular displacement measuring instrument can be constructed by attaching pick-offs at the gimbal bearings of the above (known as a free gyro, Figure 31), and if mounted in a missile, would detect the angles through which it was turning with respect to the "fixed" direction of the rotor axis, in one or two planes, according to the number of degrees of freedom.

104. Practical instruments do not, of course, have friction-free pivots, a perfectly balanced rotor, or friction-free gimbal bearings. The bearing friction, mass imbalances, the addition of angular measurement pick-offs all result in perturbations to the pointing direction - "drift". The "drift rate" is the single most important figure characterising the performance of a gyroscope.

The Rate Gyroscope

105. An important property of gyroscopes is the way they respond to applied torques. Instead of their responding by turning in the direction of the torque, as might be expected, they turn about an axis perpendicular to both the axis of the applied torque and the gyroscope's angular momentum vector.

106. This effect, called precession, forms the basis for some types of instruments, for instance the rate gyroscope. This is a one-degree of freedom design, which responds to angular rates applied to the "input" axis - perpendicular to both the rotor spin axis and the gimbal axis - by turning about the gimbal axis. In fact this turning torque is balanced out by a spring force or torque bar, the rotation of which is measured.

The Integrating Gyroscope

107. The single degree of freedom floated gyroscope, also called the hermetically sealed integrating gyroscope, has widespread use in ballistic missile guidance packages because of its extremely high accuracy.

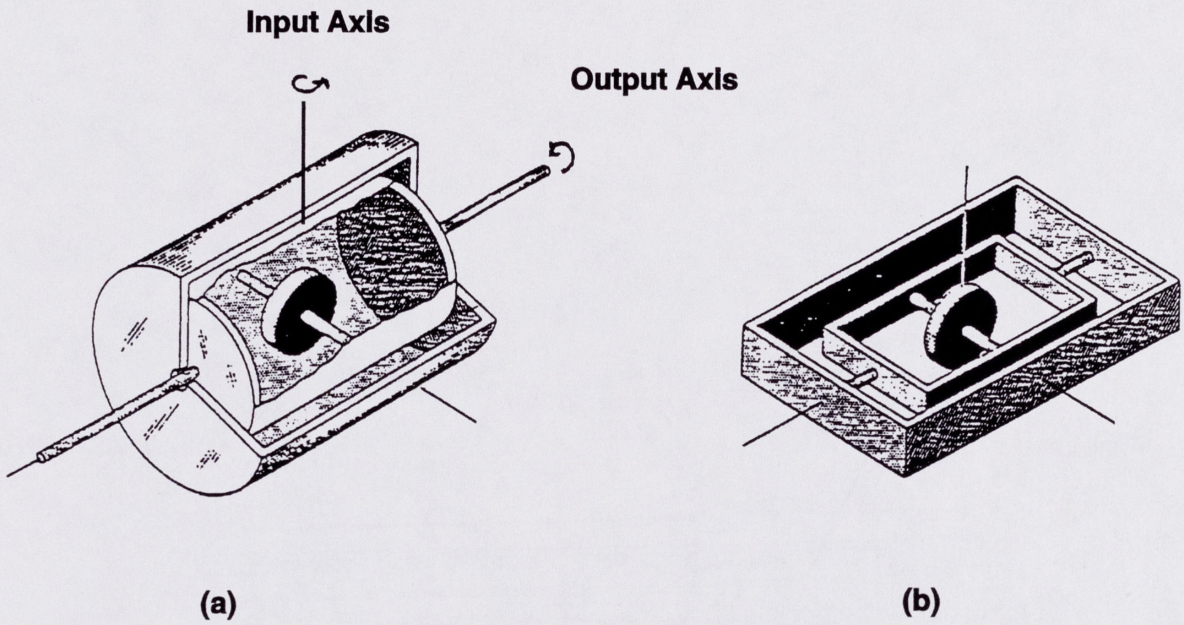


Figure 32a Mechanism of Operation for a Rate Integrating Gyroscope (shown schematically)

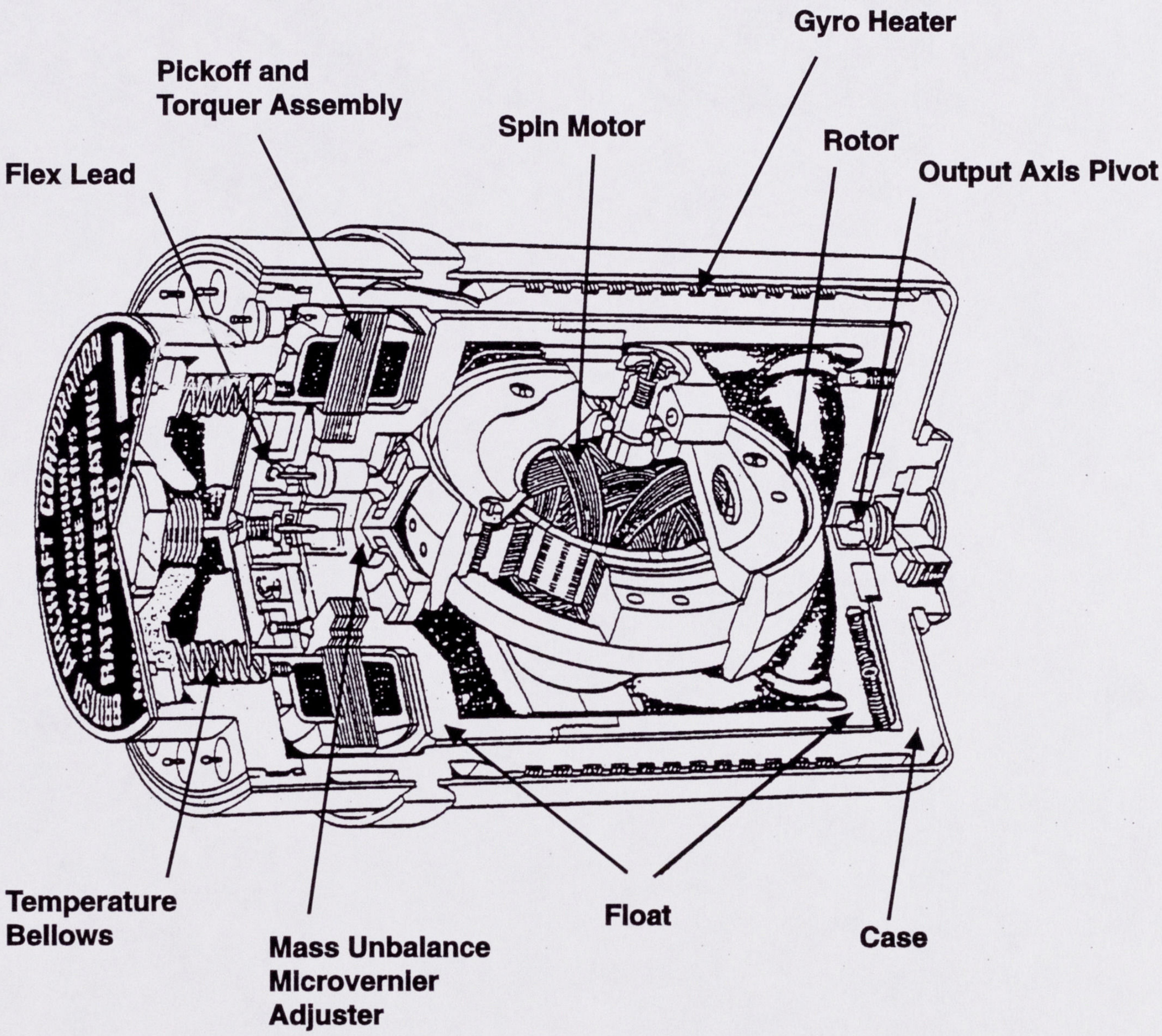


Figure 32b   Section Through a Rate Integrating Gyroscope

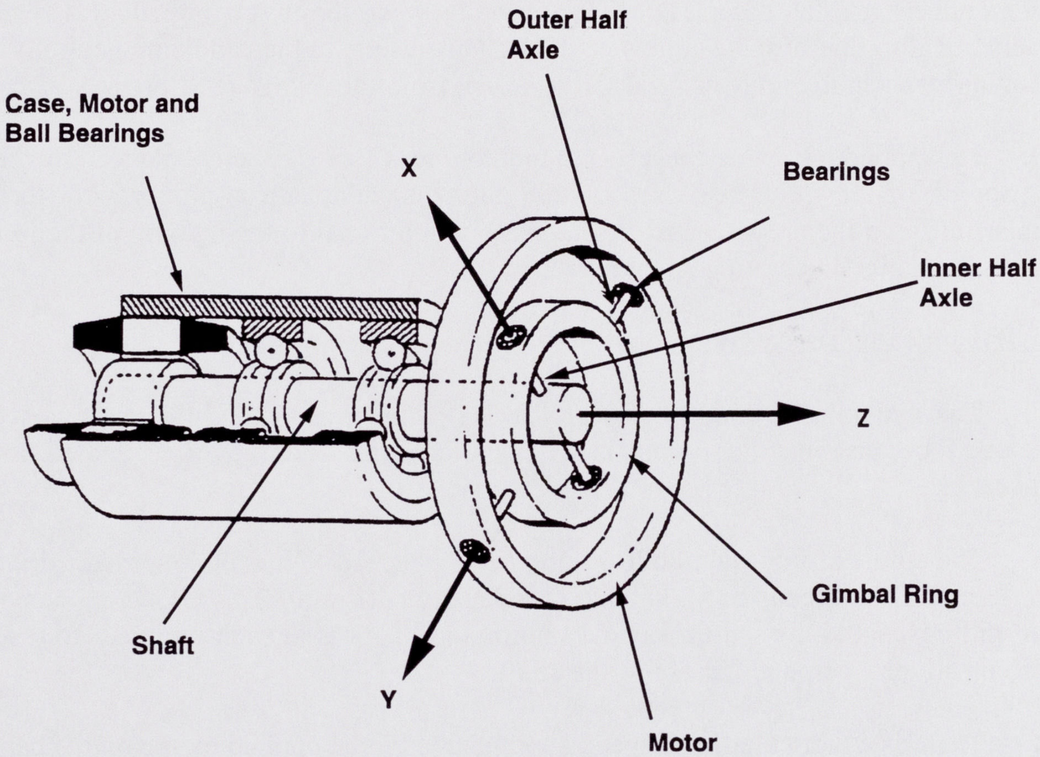


Figure 33a Dynamically Tuned Gyroscope

108. The gyroscope rotor, part of a synchronous electric motor, is mounted cross-wise in a hermetically sealed cylindrical can filled with inert gas. This can has pivots at both ends which connect it to an outer casing, the space between the two being filled with a fluid of density equal to that of the can plus contents. This results in the can being neutrally buoyant, removing its weight, and hence frictional torque, from the pivots. (See Figures 32a and 32b).

109. An applied input rate causes an output torque which is exactly balanced by the viscous drag torque of the fluid. At this point the output angular rate is proportional to the input angular rate, and the output angle of rotation is proportional to the integral of the input rate – hence the name "integrating gyroscope".

The Dynamically Tuned Gyroscope

110. The dynamically tuned gyroscope (DTG), sometimes called the dry gyroscope, was developed because of the problems in manufacturing and repairing floated integrating gyroscopes.

111. The rotor, of unusual "hollow" design, is attached to a central spindle (driven by an electric motor) by means of a gimballed torsionally stiff joint. This allows movement of the rotor with respect to the shaft about axes normal to it, but is of such design as to tend to keep the rotor aligned perpendicularly to the shaft.

112. There is a particular rotor speed at which the torque applied by the pivots balances the dynamic torque, which has the effect of making the rotor behave as if it were freely suspended – the gyroscope is "dynamically tuned". Two sets of pick-offs detect rotor displacement, so it is of the two degree of freedom type. Control or restoring torques are provided by external coils which act on magnets set into the rotor. (See Figures 33a and 33b).

Vertical Gyroscopes

113. Vertical gyroscopes are a modification of the two degree of freedom design. By incorporating a gravity sensor on the inner gimbal, they measure angular deviation from the local vertical, and are frequently to be found in less-sophisticated ballistic missiles.

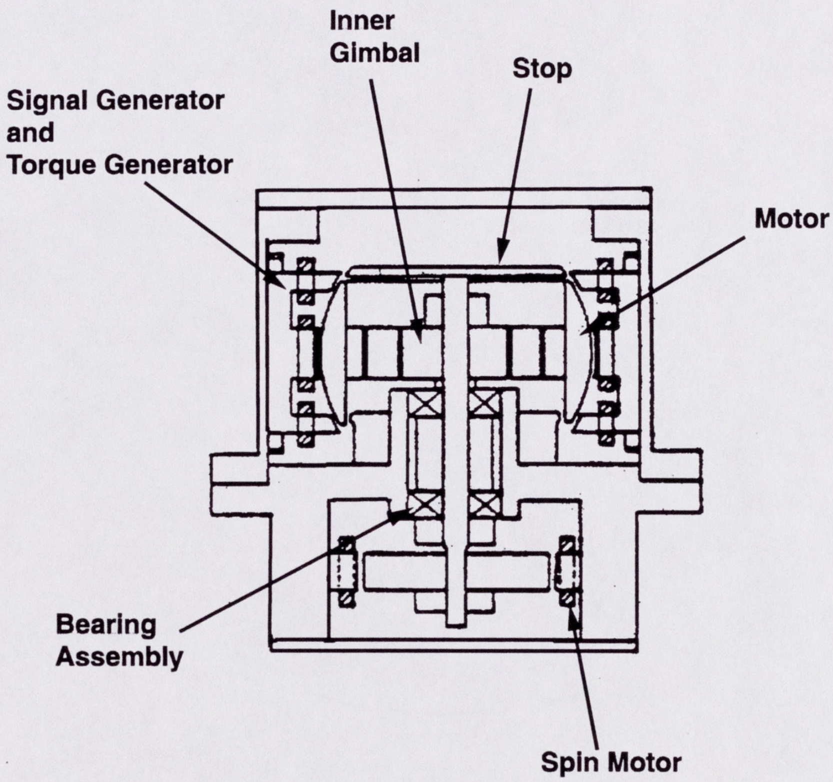


Figure 33b Cross Section of Typical DTG Configuration

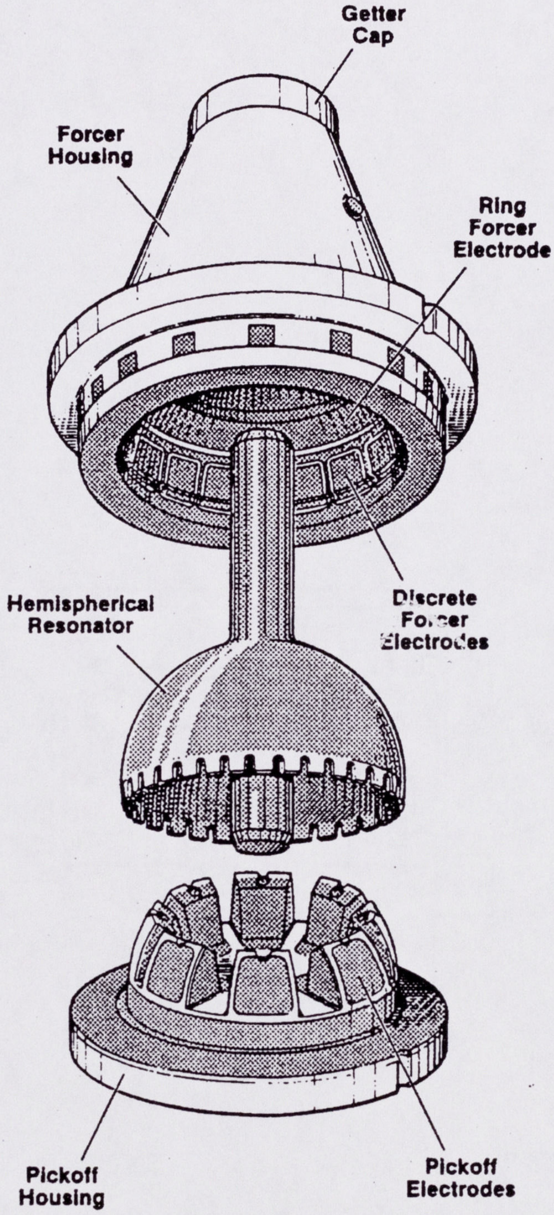


Figure 34 Hemispherical Resonator Gyroscope - Component Parts

– Inertial Oscillating (Vibrating Mass) Gyroscopes

Hemispherical Resonator Gyroscopes

114. This gyroscope utilizes the effect that a pattern of stationary ('standing') wave vibrations set up in an object moves when the object is rotated. Measurement of changes in the positions of the wave 'nodes' enable the applied rates to be determined.

115. Vibrations are excited electrostatically in the gyroscope's curved quartz 'resonator', and the wave positions monitored (also electrostatically) to give a direct measurement of input rotation rates (see Figure 34).

116. This type of instrument has many advantages – a very fast response, high accuracy, and ruggedness. Its technology is not fully developed yet, but examples of gyroscopes based on these principles can be expected to appear in high–accuracy strapdown platforms.

– New Technology Gyroscopes (Optical)

117. Many modern gyroscopes do not in fact rely on these mechanical principles, as other effects produced by rotation have been exploited to form the basis of angular measurement sensors. They are known as non–inertial gyroscopes.

Optical Gyroscopes

118. Optical gyroscopes do not contain any high inertia rotating masses, and rely on a completely different principle of operation – the fact that the "path length" covered by a beam of light between two points a fixed distance apart is affected by the motion of those points.

119. When the path lies in a plane, and is "closed" ie. the light travels round the path and returns to its starting point, enclosing an area, the path length is proportional to the rate of rotation of the plane (relative to inertial space). This is known as the Sagnac effect. It is utilized by ring laser and fibre optic gyroscopes (see below).

120. In both cases a coherent ("in–phase") light beam is split into two, and the parts sent different ways round a closed path, then compared and the phase differences (which corresponds to optical path differences) measured, enabling the instrument rotation rate to be derived directly.

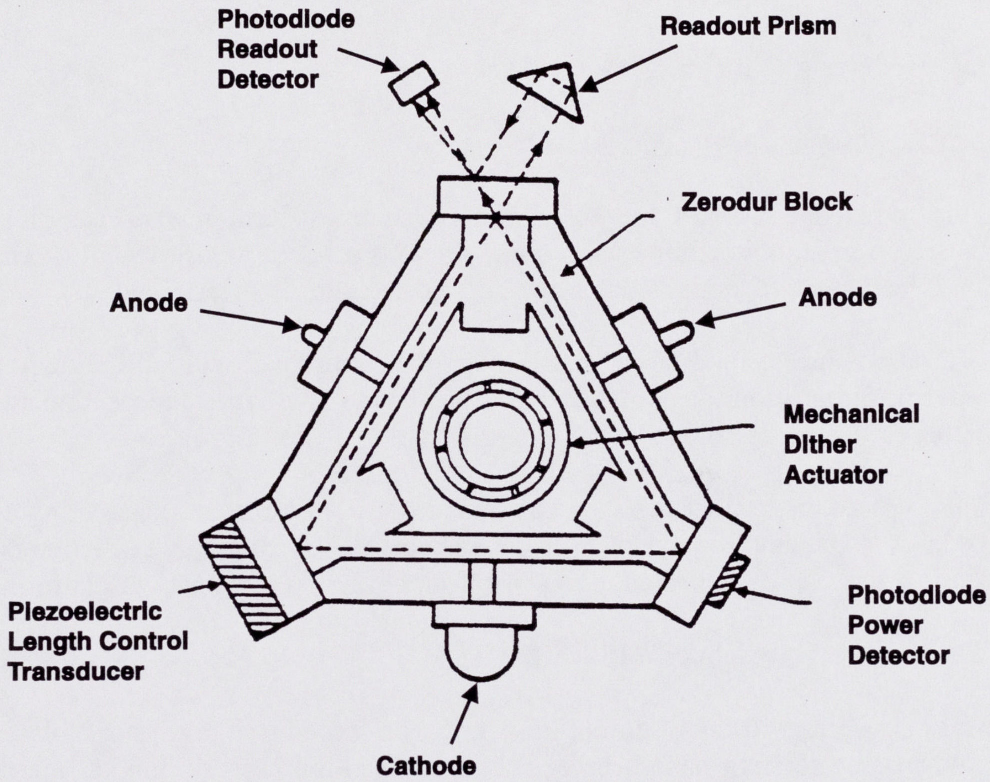


Figure 35 Triangular Laser Gyroscope Assembly

Ring Laser Gyroscopes

121. In ring laser gyroscopes the optical path usually comprises three gas-filled glass "cavities" arranged in the shape of a triangle, with mirrors at the vertices. These "optical" cavities are laser generators which are designed to produce the two oppositely propagating beams. A proportion of each beam exits from the "ring" into a detector where the beams are recombined. The relative phase shifts, and hence the required rotation rate are determined from measurements of the resulting interference fringe pattern. (See Figure 35).

122. There are many problems associated with the manufacture and operation of these instruments, due to their complexity. Once they are overcome the result is an extremely high performance rugged device well suited to ballistic missiles.

Fibre Optic Gyroscopes

123. Fibre optic gyroscopes are similar to ring laser gyroscopes, and work on the same principle. Coiled optical fibres take the place of the cavities, and the propagating light beams created externally by a semiconductor laser.

124. These sensors have the advantage of being small and compact (ring laser gyroscopes by comparison are extremely bulky), and in many ways suited to missile use, but as of yet the technology is still unproven and difficulties are encountered with their production - particularly for the associated electronics. There is some doubt over whether they can be made to meet the demanding requirements of missile use, though there is considerable potential for them.

- Accelerometers

125. Accelerometers sense translational acceleration (in one axis). They have a vital role to play in ballistic missiles, as positional and velocity details of engine cut-off have to be known precisely, and it is a critical factor determining missile accuracy.

126. There are two main types of accelerometers, "open loop" and "servo-force balance". In the former, acceleration causes the movement of a mass against an elastic restraining force, and the displacement is measured to derive the input. In the latter, the mass is constrained from moving far by a feed-back restorative mechanism activated by the displacement measuring sensor.

- All inertial accelerometers use "F = m.a" or "T = d/dt(I.ω)"
- Most basic accelerometer (not practical!)

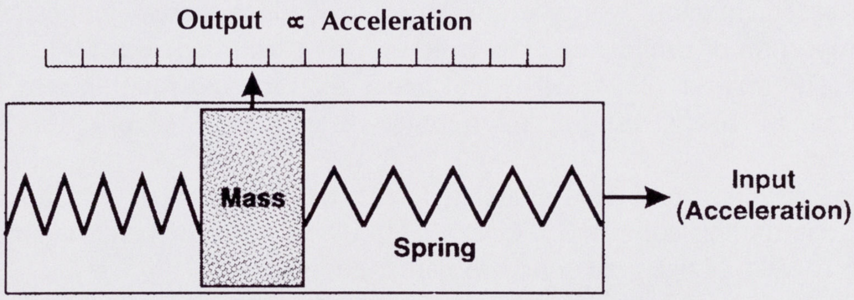


Figure 36 Schematic Accelerometer Design

127. Simple open–loop devices take the form of a mass held in a horizontal channel by restraining springs, with the acceleration being measured by movement of the mass as indicated on a mounted potentiometer pick–off (figure 36), or a simple pendulum in the vertical plane sensing horizontal acceleration and read off by a connected pointer moving over a circular potentiometer track.

128. A pendulous servo–force balance closed loop accelerometer in common use consists of a pivot mounted pendulum held in a null position between two permanent magnets. Control is by a feed–back current through an electromagnet mounted on pendulum shaft. This is caused by movement of the pendulum mounted pick–off over a potentiometer. (See Figure 37). This type of accelerometer is most often used for sensing single axis inputs. Two axis versions are seen but they are considerably more complex and difficult to manufacture.

129. A very sensitive acceleration sensing instrument known as the pendulous integrating gyroscopic accelerometer (PIGA) has become widely adopted for long–range ballistic missile guidance. The basis of the design is a single degree of freedom integrating gyroscope, with a pendulous mass attached to the float. As a result, during acceleration the float chamber is caused to rotate. This movement is sensed by a signal generator which feeds a torque motor on the gyro input axis opposing it. This input angular rate is proportional to the initial acceleration. (See Figure 38).

– Inertial Guidance Instrument Performance

130. The principal parameters for both gyroscopes and accelerometers, given in Figure 39, specify their capabilities. They are defined in terms of applied rate and measured rate, and applied acceleration and measured acceleration, for the gyroscopes and accelerometers respectively. The definitions are given graphically in Figures 40a to 40e. The required values for ballistic missile 'inertial grade' instruments are given in Figure 41 for the case of a typical intermediate range case. Figures 42 and 43 show, more generally, the types of applications for instruments of differing sensitivities. This information is given by application in Figures 44a,44b, and 45a,45b for gyroscopes and accelerometers respectively.

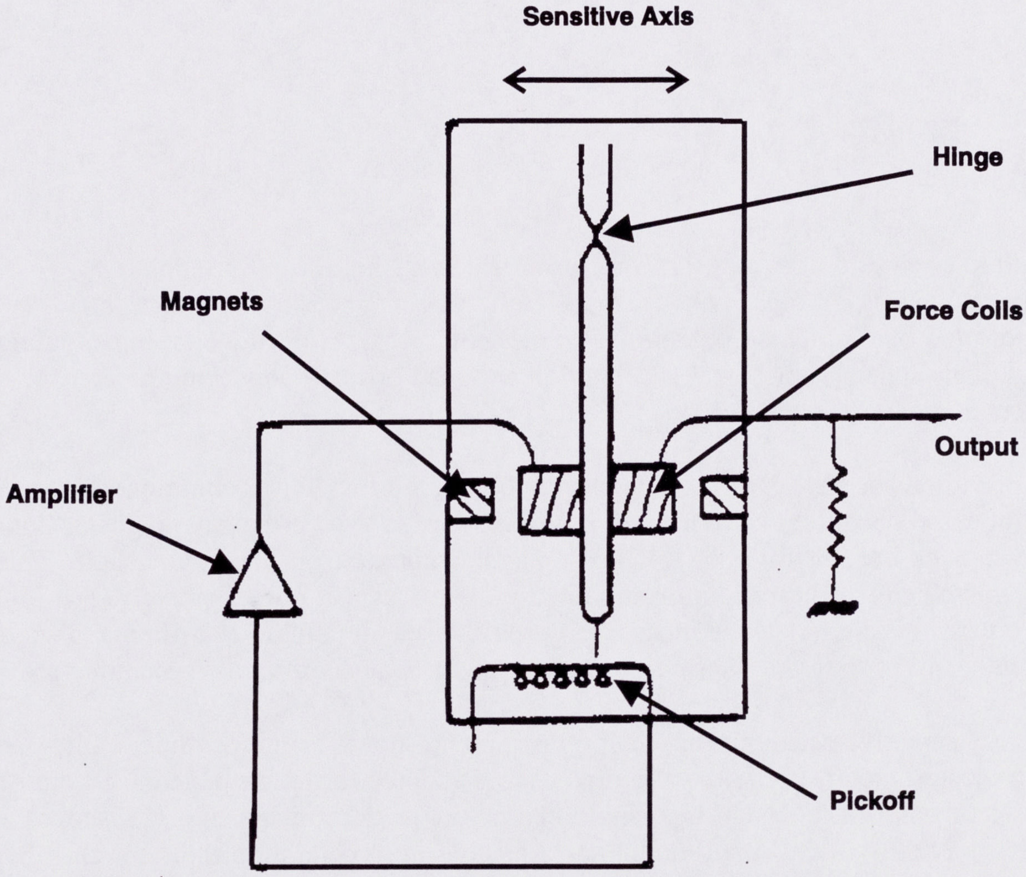


Figure 37 Simple Forced Pendulum Accelerometer

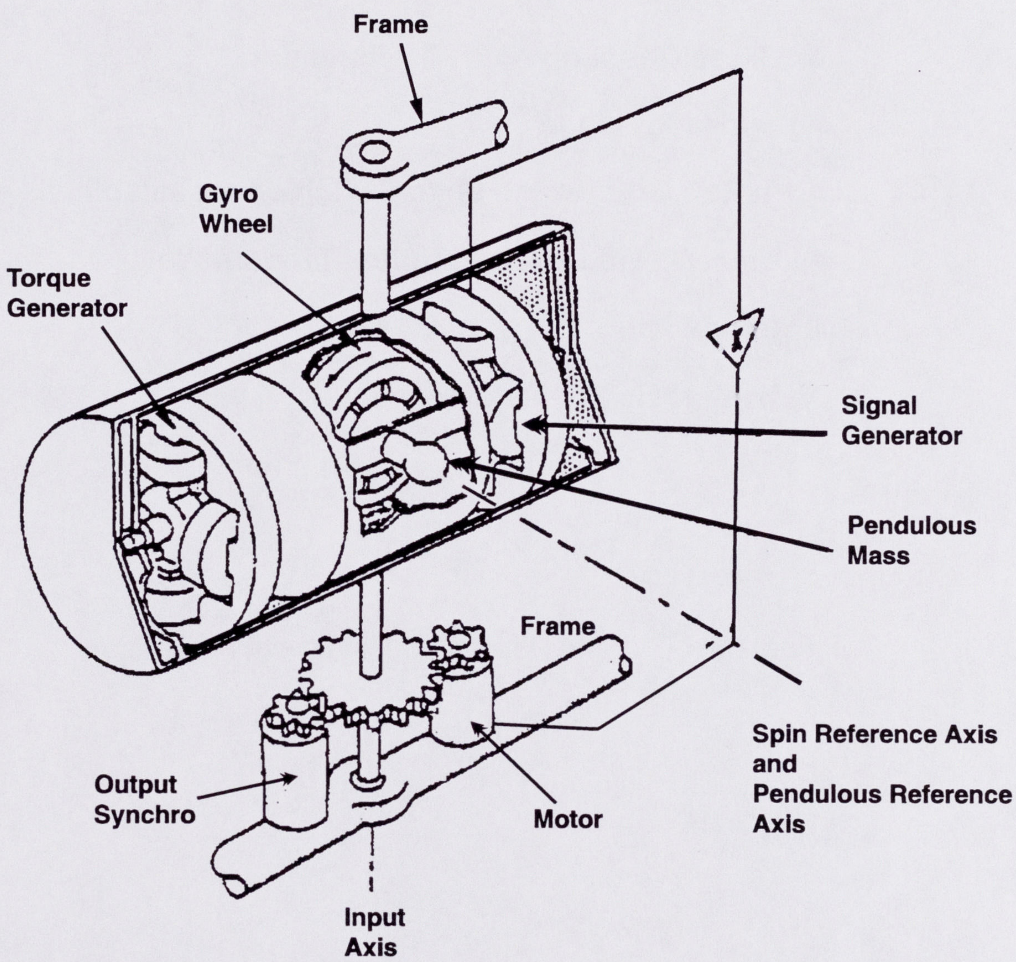


Figure 38 Pendulous Integrating Gyroscope Accelerometer

- **Scale Factor/Linearity**
- **Bias/Zero Offset**
- **Activation Time**
- **Cross Coupling/Axis Misalignment**
- **Dynamic Range**
- **In Run Drift/Switch on to Switch on repeatability**
- **Noise/Noise under Vibration/Random Walk**
- **Bandwidth**
- **Hysteresis/Resolution**

Figure 39 Inertial Guidance Instrument Parameters

Bias/zero offset

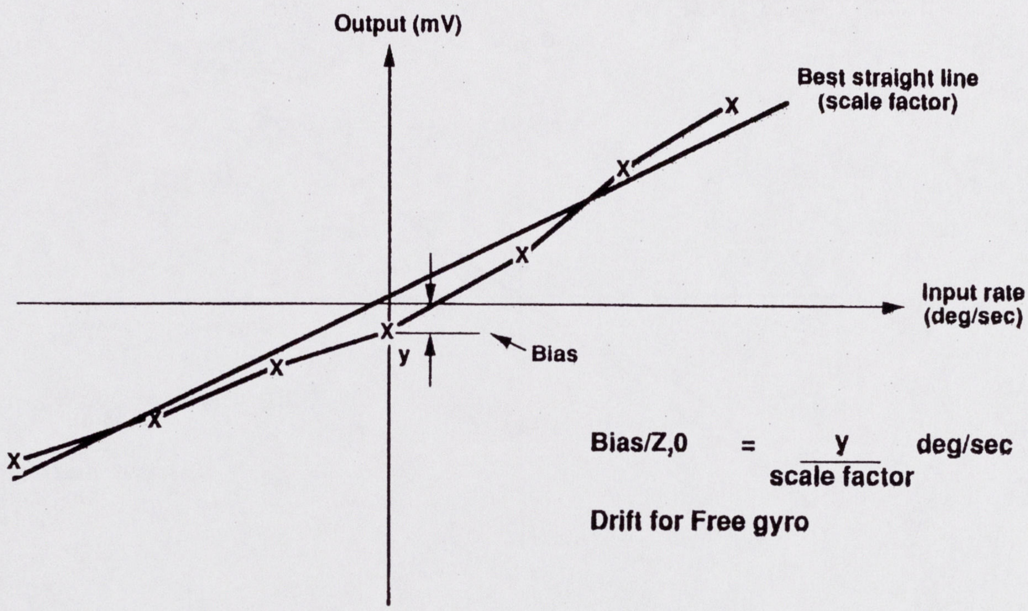


Figure 40a Definition of Terms (1)

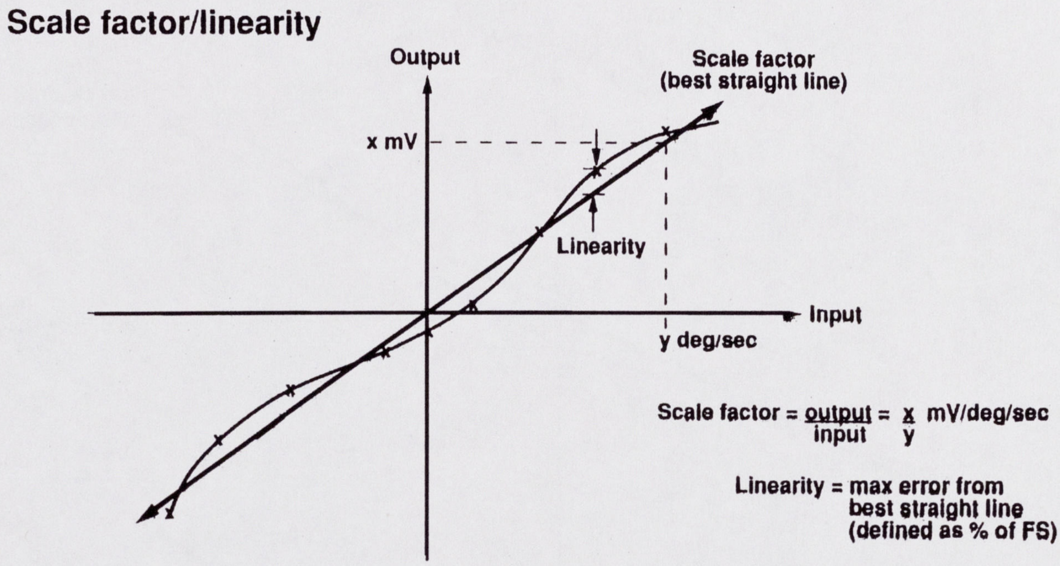


Figure 40b Definition of Terms (2)

In-Run Drift/Switch-on to Switch-on Repeatability

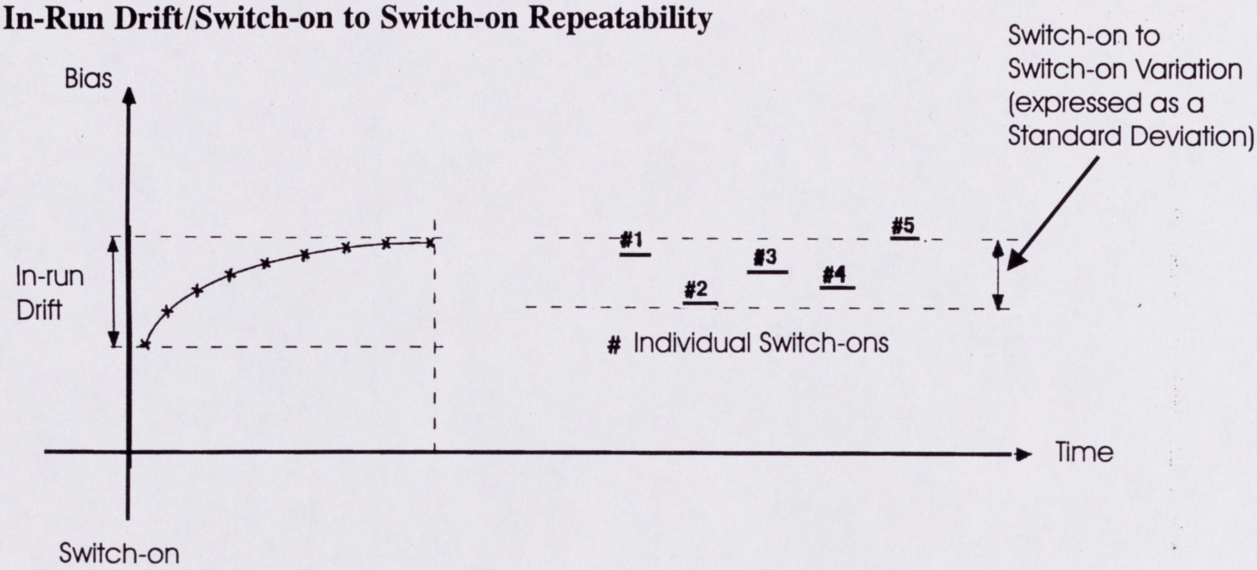


Figure 40c Definition of Terms (3)

Hysteresis/Resolution

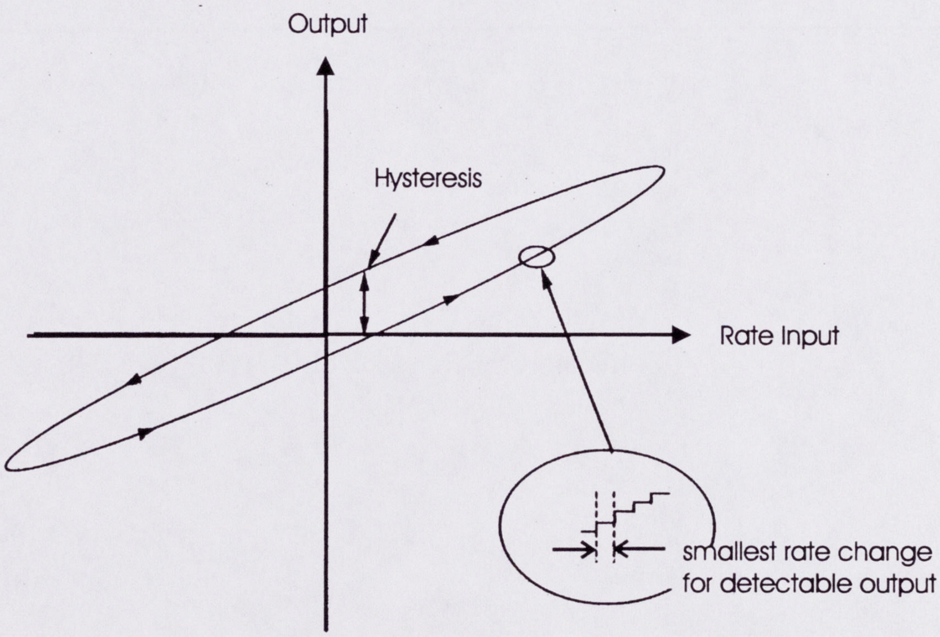


Figure 40d   Definition of Terms (4)

Cross-coupling/Axis Misalignments

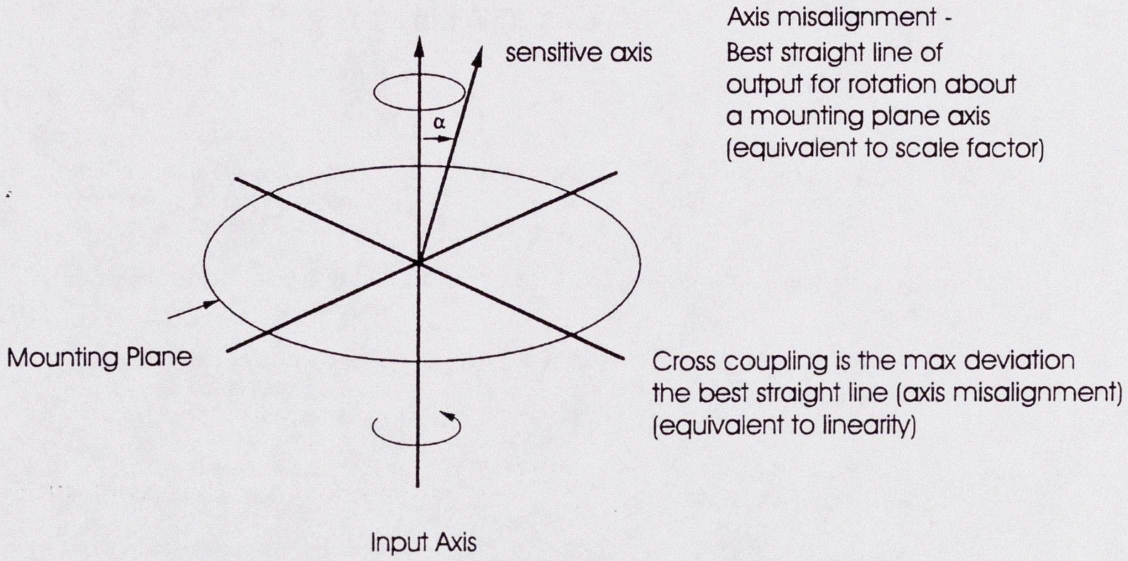


Figure 40e Definition of Terms (5)

ERROR BUDGET	3000 - 10000 km Range	COMMENTS
Gyro Bias and G Sensitive Gyro Drift (Degrees/Hour)	0.01 - 0.001	Stability of these terms affect calibration frequency requirements for conventional gyros.
Gyro Scale Factor (PPM) Linearity	2 - 20	Scale factor is most critical in strapdown.
Random Walk (Degrees/Root Hour)	0.01 - 0.001	Alignment time principally affects azimuth accuracy when gyrocompassing employed.
Accelerometer Dynamic Range (Microgee's to G's)	10^6 - 10	Gyro accelerometer ideally suited for this application.
Accelerometer Scale Factor Linearity (ppm)	50 - 2	Most critical parameter at these ranges. Field calibration is feasible.
Accelerometer Bias Stability (Micro g's)	100 - 5	Field calibration is feasible.
Alignment stability between sensors (arc minutes)	1 - 0.01	Critical characteristic in strapdown systems. Stability is essential.

Figure 41 Ballistic Missile Guidance Instrument Error Budget

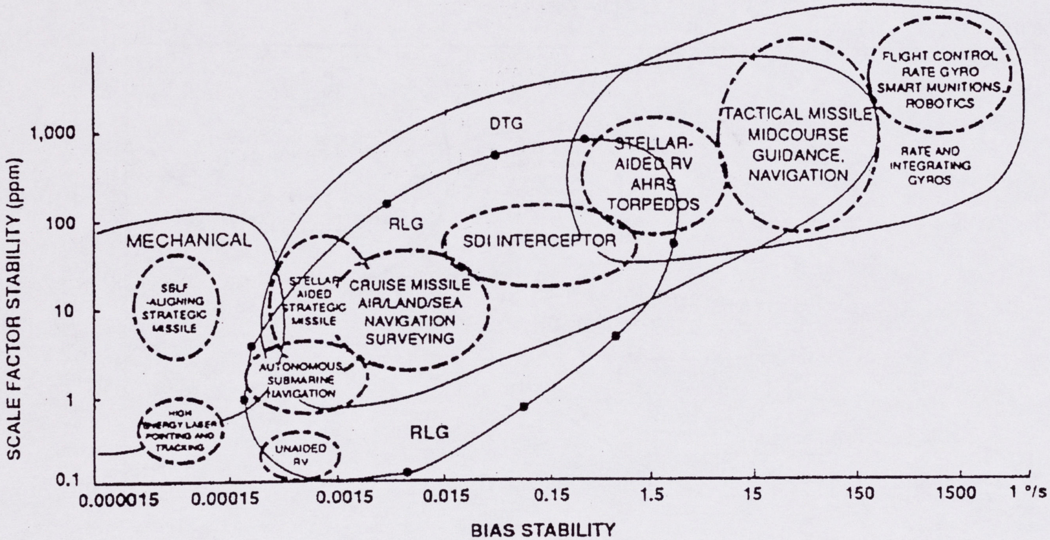


Figure 42 Current Gyroscope Applications Sensitivity Requirements

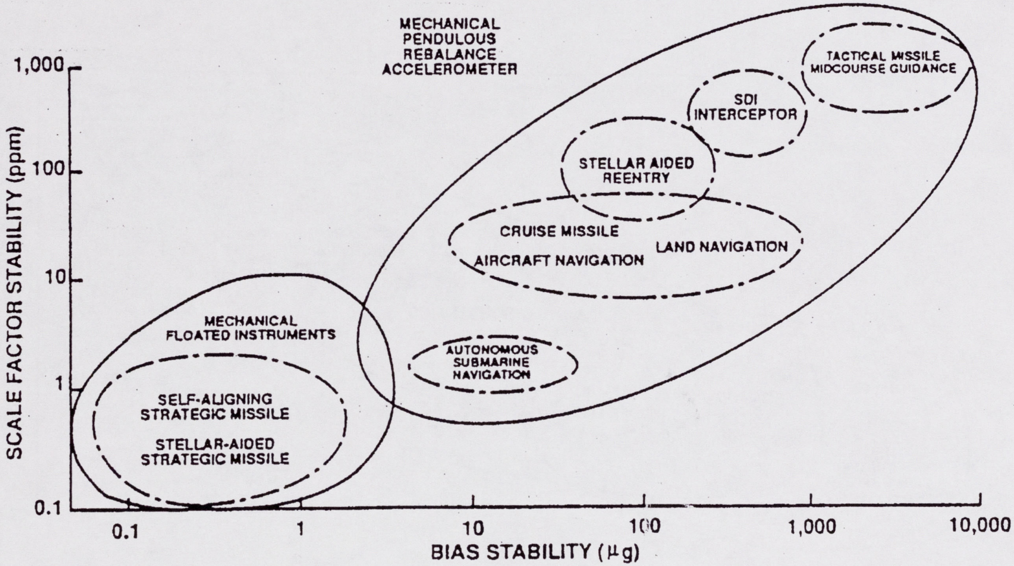


Figure 43 Current Accelerometer Applications Sensitivity Requirements

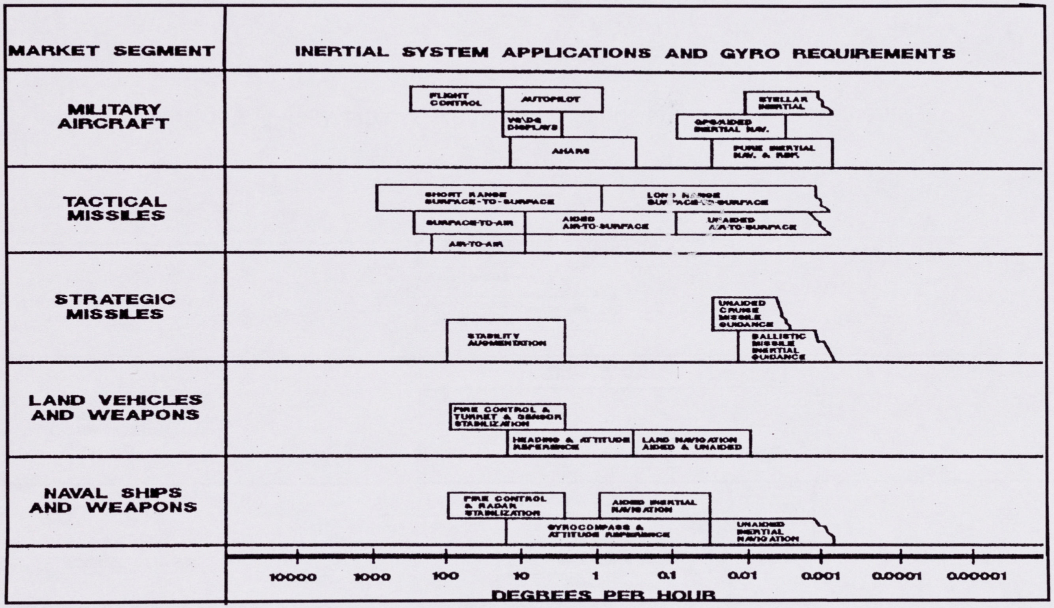


Figure 44a Inertial Systems Applications and Gyro Requirements (1)

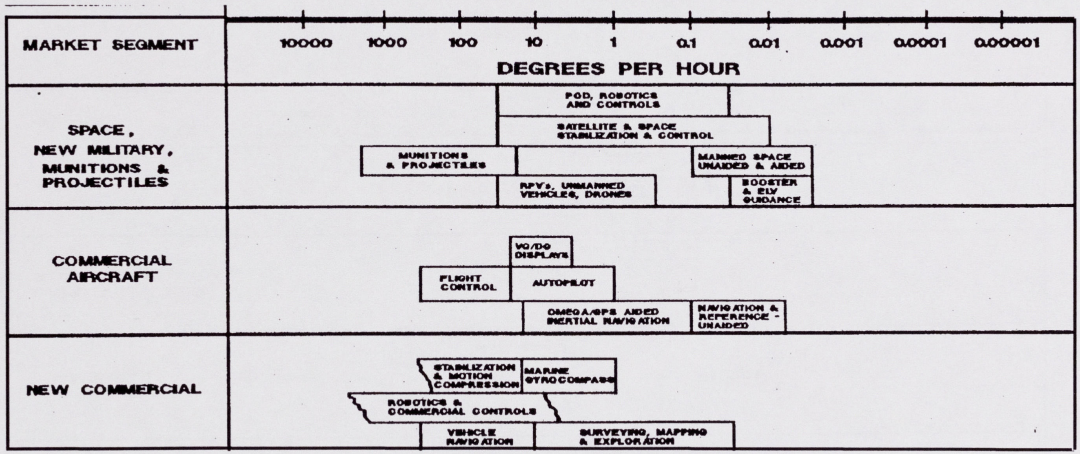


Figure 44b Inertial Systems Applications and Gyro Requirements (2)

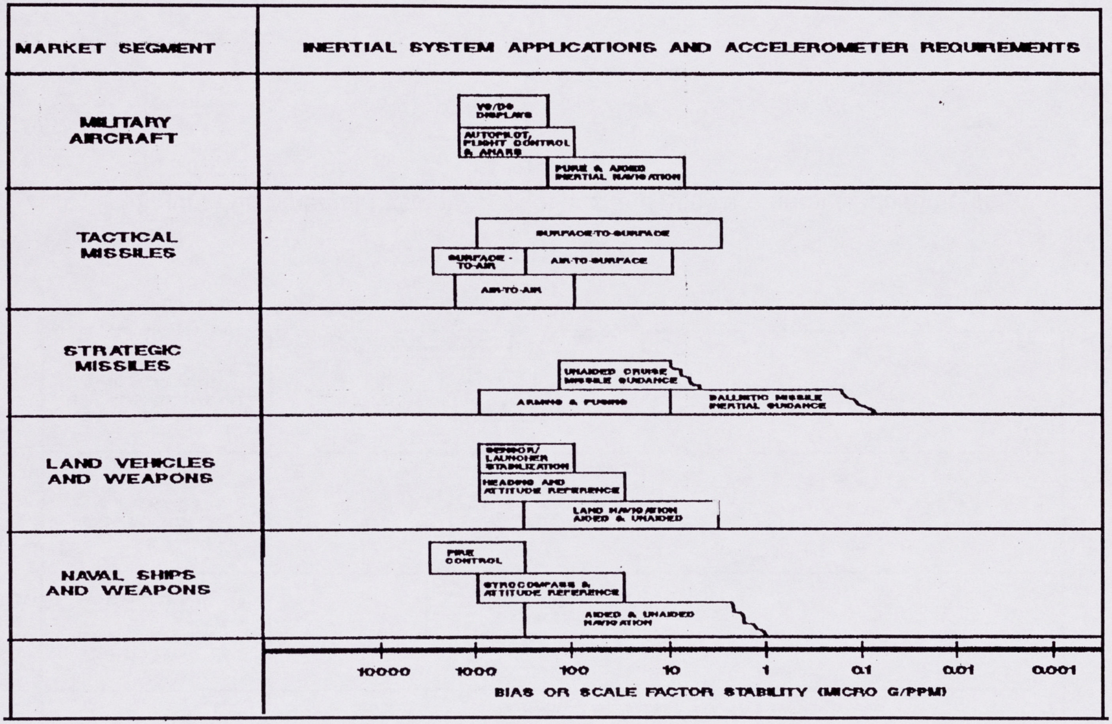


Figure 45a Inertial System Applications and Accelerometer Requirements

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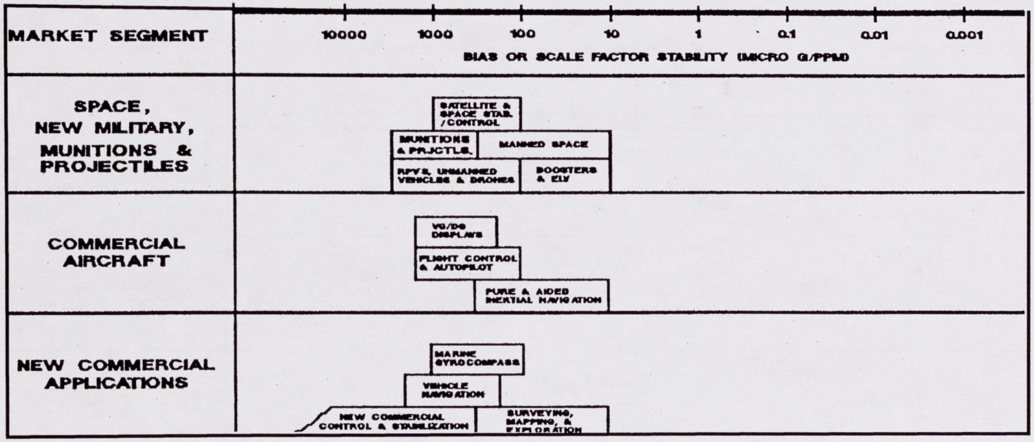


Figure 45b   Inertial System Applications and Accelerometer Requirements

131. The accuracy of inertial navigation systems tends to drift with time, leading to discrepancies between the actual and calculated positions of the missile. These discrepancies can be compounded if the missile is launched from a location whose coordinates are themselves inaccurate. For this reason, information obtained from navigation satellites is increasingly being used to correct the inertial navigation systems both before and after launch.

132. Navigation satellites continually broadcast their identity, their position (based on an almanac which is up-loaded from ground control stations on a regular basis), the time (taken from an on-board clock), and the positions of the other satellites in the constellation. A satellite navigation receiver in a ballistic missile compares the message from three or more satellites - either sequentially or in parallel - and carries out a simple triangulation calculation to determine the position of the missile based upon the positions of the satellites and the delay in receiving their signals. This position can be calculated within a few seconds on a world-wide, continuous and all-weather basis. It is also worth noting that such receivers are passive - this means that they do not interrogate the satellites themselves, but merely listen for a message.

133. Two global satellite navigation systems already exist - the American Global Positioning System (GPS, also known as NAVSTAR) and the Russian Global Navigation System (GLONASS - also referred to by the Russians as URAGAN). Other navigation satellite systems are being developed by China and Japan for local use.

134. The commonly available civil signals from both GPS and GLONASS provide locations to an accuracy of a few tens of metres. The addition of separate military signals allows accuracies of a few metres to be achieved by eliminating ionospheric delays from the signals and thus increasing the accuracy of the time measurement. New 'differential' techniques can however, allow civil equipment to achieve greater than military accuracy - of the order of a metre or less.

135. Both GPS and GLONASS are controlled by the military forces of their respective countries, although there has been pressure from the civil user community for both systems to come under civil control. GPS was declared fully operational two years ago; the GLONASS system is expected to be complete at the end of this year. It's important to note that the number of operational GLONASS satellites has been maintained despite the collapse of the Soviet Union.

136. To reduce vulnerability to ECM, satellite navigation receivers fitted to ballistic missiles might well be narrow beam and single channel – meaning that signals can be received from only one satellite at a time. The missile body would have to rotate whilst in flight, pointing the satellite navigation antenna at each satellite in turn in order to pick up a signal. This would, of course, take a few minutes to accomplish and might lead to a slightly more ambiguous answer than a multi–channel receiver would provide.

STRUCTURE AND MATERIALS TECHNOLOGY

– Introduction

137. At launch a missile experiences loads and vibrations applied suddenly to the structure by the main engines. The axial acceleration produces a load factor which is a function of the thrust force, aerodynamic drag and the vehicle weight.

138. Another critical time occurs shortly afterwards, when, as the missile rises vertically, maximum dynamic pressure is encountered. It is characterised by large bending moments, aerodynamic forces and temperature changes. Further severe stressing is experienced at first stage burn–out/stage separation, during manoeuvre (as a result of missile flexing) and at stage separation.

139. A full understanding of the mission requirements in terms of payload, range and trajectory profile is required before any progress towards a preliminary design can be made. The objective of much of the design effort is, as far as is possible, to develop a vehicle of smallest mass, size and cost that will meet the basic requirements.

– Airframe Structural Design

140. The structural design of a missile begins with the assessment of possible layouts of basic skeletal form, load bearing members and external surface, which together making up the 'airframe'.

141. From the payload/range requirement, figures characterising the possible configurations of vehicle type, dimensions, stage masses, engines and propellant masses and trajectory dynamic profile may be derived.

142. The design progresses to the construction of structural models of possible airframe, engines, fuel tanks and subsystem combinations, which can then be tested by running computer simulations of their expected flight behaviour and envisaged loadings.

143. The vibrations experienced during flight can result in the generation of resonances which can lead to excessive loads on parts of the structure. Being extremely difficult to predict and model, resonances are a principal cause of flight failures.

144. The designer has to assess each selected structure to determine its natural oscillation frequencies and the vibration modes, which are normally composed of two principal components, bending and longitudinal.

145. In the case of liquid fuelled missiles, special consideration has to be given to maintaining structural rigidity due to the use of relatively thin storage tanks. They would normally be pressurised to increase their resistance to buckling, but this leads to additional internal loads which have to be accommodated. Another consideration is propellant sloshing which, because of the masses involved, can lead to large oscillatory loads.

146. Aerodynamic heating causes thermal stresses due to differential expansion and changes in the mechanical properties of materials. Thermal response modelling of a projected structure is an essential part of the overall design process.

– Airframe Construction

147. Early (liquid fuelled) missiles were constructed out of thin metal sheets welded or riveted onto a framework of hoops and longitudinal stiffening struts. In some cases further strengthening was required and this could be introduced by the use of corrugated skin sections or the attachment of the outer surfaces to internal fittings such as fuel tanks.

148. Later designs incorporated reduced thickness (and lower weight) outer skins and fuel tanks, the latter being pressurised to increase the overall airframe strength.

149. Solid fuelled missiles derive significant structural rigidity from the heavy motor cases, and the external framework is simpler, usually just welded or rivetted thin sheet.

– Airframe Materials

150. Aluminium alloys are used widely for the construction of missile airframes because of their properties of relatively low density (typically 2800 kg/m^{3}), high strength (450 Mpa UTS or Ultimate Test Strength) and good corrosion resistance.

151. High strength, low alloy steels (HSLA) were developed forty years ago, with strengths of up to 1950 Mpa they have are very suitable for ballistic missile construction. Another candidate is maraging steel, an iron–nickel alloy with a strength up to 2100 MPa. Both are competitive with aluminium alloys for this purpose, being of similar cost but having superior strength to weight ratio, stiffness and temperature resistance.

152. Maraging steel, being the more expensive, is normally reserved for uses where its high strength is of particular value. As with HSLA, it can be formed into missile bodies by modern flow-forming techniques which not only increase a material's strength but can also produce very accurately shaped sections.

153. Internal structures in ballistic missiles are sometimes made with aluminium honeycomb sandwich panel. A honeycomb structure is filled with rigid plastic foam, and faced with high strength aluminium sheet, resulting in a member with higher strength to weight ratio and stiffness than solid aluminium alloy.

154. Composite materials are being employed in the manufacture of missile parts to an increasing extent. Already widely used for solid rocket motor cases they can sometimes also serve as the missile outer surface. Filament fibre wound epoxy is a particularly good example of these materials with missile applications, offering great strength for low weight.

PAYLOAD TECHNOLOGY

- Introduction

155. The payload consists of the missile warhead, the fuzing and arming mechanism, a supporting structure and, usually, an external heatshield. There are two basic types – 'non-separating', which is part of the missile body, and 'separating', which detaches during free flight prior to the final phase of the flight path to follow its own trajectory . In the latter case the separating warhead plus structure/electronics/heatshield is referred to as a re-entry vehicle (RV).

156. Generally short range ballistic missiles, which for the most part of their flight remain within the earth's atmosphere have non-separating warheads. Longer range missiles fly some of their trajectory exo-atmospherically and reenter at very high speeds (typically 3 to 6 km/s). Considerable improvements in stability and accuracy can be obtained by detaching the warhead prior to re-entry.

157. The use of a separating warhead leads to considerably greater complexity in the overall missile design. A mechanism to effect the RV separation is required, which must operate in a very precise manner, to ensure it is ejected smoothly at the correct moment on the trajectory, without colliding with other parts of the missile.

158. Many missiles mount multiple RVs (sometimes denoted 'MRVs'), in a manner which enables them to be released individually by separate mechanisms. In some cases a post-boost vehicle 'PBV', often referred to as a 'bus', is used to dispense them. The bus would have thrusters giving it an ability to manoeuvre in space, and its warheads would be deployed in different directions with varying velocities. This results in a spread of the corresponding ground impact points, enabling several different targets to be attacked simultaneously. Configurations of this type are referred to as Multiple Independently Targeted Re-entry Vehicles (MIRVs).

159. A further development is to have RVs which, once deployed, do not fly ballistically to the target, but effect some trajectory manoeuvres (usually by inducing lateral aerodynamic forces on re-entry). These are called MARVs, from MAnoeuvring Re-entry Vehicles. These are designed either to defeat defensive anti-ballistic missile systems whose operation relies on some form RV trajectory prediction, or to improve targeting accuracy by utilising some form of terminal guidance.

- RV/Warhead Heatshields

160. Thermal protection is required for the warhead and its internal sub-systems on reentering the Earth's atmosphere, when severe heating results from the frictional effects experienced at speeds of 4 km/s and above. This is provided by an external heatshield, which reduces the heat flow from the surface to the interior. This can be achieved in different ways - insulation, ablation or a combination of the two being most common. The necessity of withstanding this environment and optimising accuracy imposes tight constraints on the design of an RV.

161. Insulation methods reduce the rate of heat flow through the shield, usually by employing ceramic type materials with very low thermal conductivity. This results in very high surface temperatures being reached. These can be reduced, at a penalty, by increasing the shield or substrate mass, creating a "heat sink".

162. Ablation techniques rely on the absorbtion of heat on the outside of the shield by means of melting, vaporisation and decomposition of surface layers. These changes can also affect the air flow round the body in a way which reduces the net heating experienced.

- Warhead Charges - Damage Mechanisms

163. There are four main types of warhead, high explosive (HE), nuclear, chemical and biological. All of them employ conventional explosive to a greater or lesser extent either to activate the device (in the nuclear case), or in some form of dispersal mechanism.

<u>High Explosive Warheads</u>

164. HE warheads may contain a single charge or several separately dispersed and detonating charges, known as submunitions. Typical compositions are either TNT or RDX (rapid detonation explosive), or fuel-air explosive (FAE).

165. The performance of general purpose HE warheads is usually judged in terms of blast effectiveness, measured as overpressure and impulse. A 40psi overpressure blast wave would completely demolish a typical unreinforced building, but not a hardened bunker. Levels above this would typically be experienced up to 7 m from the explosion of a warhead containing 100 lb of HE or up to 13 m for a 1000 lb case. Only 5-10 psi overpressure would be sufficient to destroy radars and vehicles (up to 15 m and 70 m respectively for the 100 lb and 1000 lb charge).

166. Different warhead designs are employed according to the particular requirements for the weapon. Fragmentation warheads utilise parts of the external casing, which readily breaks into small pieces to form projectiles for use against personnel or armour. Inert fragments may also be mixed with the explosive to increase the overall effectiveness.

167. A layer of incendiary material may be bonded to the warhead outer casing, as it has been found that this extends the useful range, penetration capabilities and effectiveness of the device against lightly armoured targets, personnel, and fuel storage tanks.

168. Fragmentation weapon performance is determined by calculating the probability of an individual fragment hitting a vital part of the target and disabling it. An important characteristic for most applications is the metal penetration depths achievable. Most 'thin–skinned' targets such as ordinary lorries and aircraft have 1/8 in. mild steel outer surfaces (or the equivalent). A 1 gm fragment would penetrate this and up to 1/20 in. of thin armour plate if travelling at over 330 m/s, but to defeat 1/3 in. armour would require a velocity of 2300 m/s.

169. Where penetration of thick walls or heavily armoured targets is required, a shaped charge design is often used. This concentrates the explosion shock waves into a convergent cone which is directed at the target. It is only likely to be in submunitions that such devices are encountered on ballistic missile warheads, as a single warhead could not be directed with the accuracy required to obtain a direct hit on the target.

170. Fuel–air explosive (FAE) warheads disperse a liquid (typically ethylene oxide) into a cloud above the target area. The resulting fuel/air mixture is then detonated by means of a catalyst or small explosion. This device produces a longer duration explosion over wider areas than the more traditional weapon and is particularly effective against people. An FAE weapon containing 1000 lb of ethylene oxide would typically yield some 3 or 4 times the total explosive impulse, at any given distance, as one containing the same mass of HE.

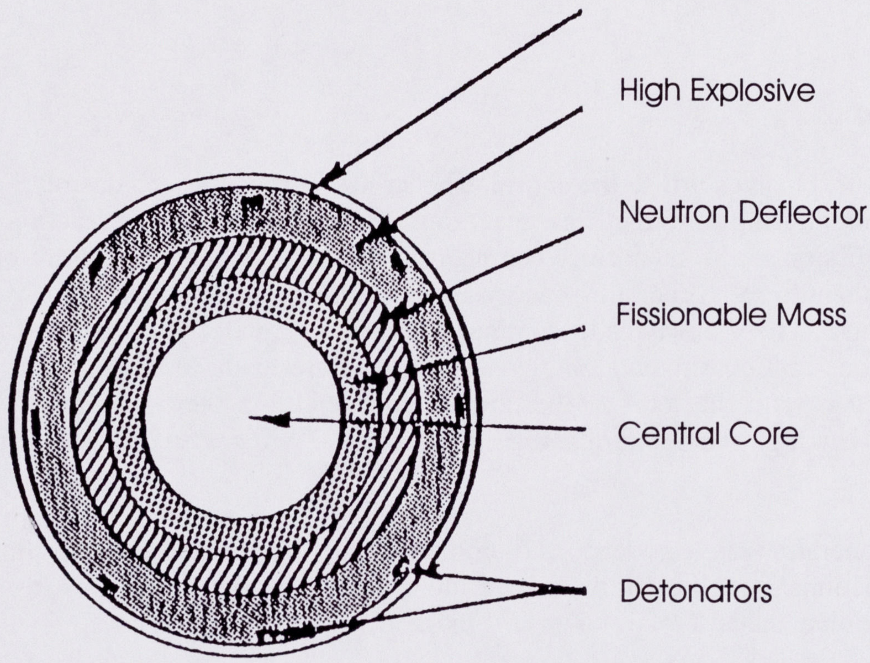


Figure 46   Cross Sectional View of a Simple Atomic Bomb

Nuclear Warheads

171. Nuclear explosives utilise the enormous energies released by the destruction of small amounts of matter during certain nuclear reactions. There are two types of reactions, "fission" and "fusion". Fission reactions occur when neutrons emitted by some nuclei hit other nuclei so as to cause them to split, liberating energy and also other neutrons, many of which produce further collisions in such a way as to continue the process by means of the so-called 'chain reaction'. Fusion reactions liberate energy when nuclei are made to coalesce into others of mass slightly less than the total of the combining nuclei. As they only take place under conditions of very high temperature and pressure, fission "trigger" reactions are required to initiate them.

172. First generation nuclear weapons (commonly called Atom or "A" bombs, utilised only the fission reactions in either Uranium or Plutonium, and released energies in the 10-100 kiloton (kT) equivalent of TNT (shown in Figure 46).

173. Second generation weapons (commonly called Hydrogen or 'H' bombs) use a fission reaction to initiate fusion reactions in a mixture of hydrogen, deuterium and tritium.

174. There is in principle no limit to the energy or yield which can be obtained from these weapons, but practical considerations of manufacture have kept most down to the 0.2 to 1 Megatons (MT), or million ton equivalent of TNT.

175. The immediate destruction caused by these nuclear weapons would depend largely on the blast and thermal effects produced. For the smaller weapons, in the 10 kT and 100 kT range, blast effects dominate. These would disable thin-skinned vehicles at distances up to 1200 m and 3000 m respectively. Thickly armoured vehicles could survive above 800 m and 1700 m respectively. For weapons at the 1 MT level, the thermal 'flash' effects dominate at the lower distances. Thin-skinned vehicles would have to be more than about 7 km away from the burst to survive, but for thickly armoured vehicles this distance is reduced to about 4 km. (These figures are rough approximations, an accurate assessment of the very complicated effects of these weapons is beyond the scope of this document).

176. Third generation weapons are those as above but with special designs to tailor the output blast/radiation spectrum to particular needs. An example of these is the neutron bomb which is more effective against people but less so against buildings than traditional devices.

Chemical Warheads

177. Chemical Warheads are used to disperse toxic chemicals, either to disable people or for "denial" to prevent the occupation of ground or the use of equipment. It can take from seconds to hours for the chemicals to become effective, depending on their type.

178. Both persistent (lasting days or weeks or longer) and non-persistent types of "agent", as the substances are called, may be used.

179. The chemical agents fall into the four categories of nerve, vesicant (blistering), nerve-vesicant, and blood, for all of which there are severe problems with handling and storage. Modern warheads use "binary" agents, stored as two usually fairly innocuous components, only becoming active on mixing.

180. The effectiveness of a given chemical weapon is very dependent on the extent to which the agent can be dispersed. The influence of the missile aerodynamics has to be accounted for to prevent the chemicals from being sucked into the wake. Usually some form of sub-munition type warhead is required with very precise control of its operation.

181. A 500 kg warhead filled with Soman or Sarin nerve agent would, if fitted to a short range ballistic missile, and exploded at low altitude over a target area, typically contaminate a roughly elliptical area (or ground 'footprint') some 2 km by 4 km. The concentrations would be such as to prove fatal to unprotected personnel over a region approximately 0.6 km by 1 km.

Biological Warheads

182. These warheads contain biological agents, which are micro-organisms or biologically derived toxins which infect living tissue. There are six types of biological agents, viz - bacteria, viruses, rickettsias, fungi, toxins and protozoa, covering a very wide lethality range.

183. A very small droplet of the more active types can be lethal if it is inhaled or comes into contact with skin - only 1 kg of these could seriously contaminate an area of 10 sq.km.

184. The dispersal problems are similar to those encountered with chemical weapons. People exposed to these agents do not become incapacitated immediately, there is an incubation period which can be as long as days or weeks.

– Fuzing and Arming Systems

185. These two systems work together to ensure the safe handling and flight of the warhead up to its place of detonation, and the actual firing of it once it is there.

186. The arming (or safety and arming) mechanism comprises one or more interlocks which prevent operation of the firing circuits or physically incapacitates the warhead – usually by incorporating mechanical blocks in the form of pins or plugs which are not physically removed until dangers to the construction or launch personnel are minimised.

187. Additional systems particularly applicable to missile warheads are those activated by acceleration, time delay, or the air pressure on the warhead during flight. These would typically be combined in series so as to allow detonation of the warhead only if all were triggered.

188. Fuzing – the detonation of the warhead at the required point – is a critical technology area for the design of ballistic missiles. There are two principle means by which it is accomplished – impact or proximity sensing.

189. Impact triggered fuzes rely on direct mechanical links, ie by some form of externally pushed rod, or by sensing the very large decelerations experienced.
This is the most basic type of fuzing, but its use does limit the role of the missile, since in many cases detonation at specific heights above ground is required to make the warhead effective.

190. Proximity fuzes utilize some form of altitude sensor. This can be done indirectly via measurement of atmospheric pressure, which, with suitable calculation and correction can be translated into height above the target. Alternatively some form of radio altimeter would be used, utilizing ground reflections of signals emitted from an on–board transmitter.

191. More sophisticated developments of this latter type employ microwave devices, and this leads to substantial improvements in accuracy, particularly at low altitudes.

APPENDIX

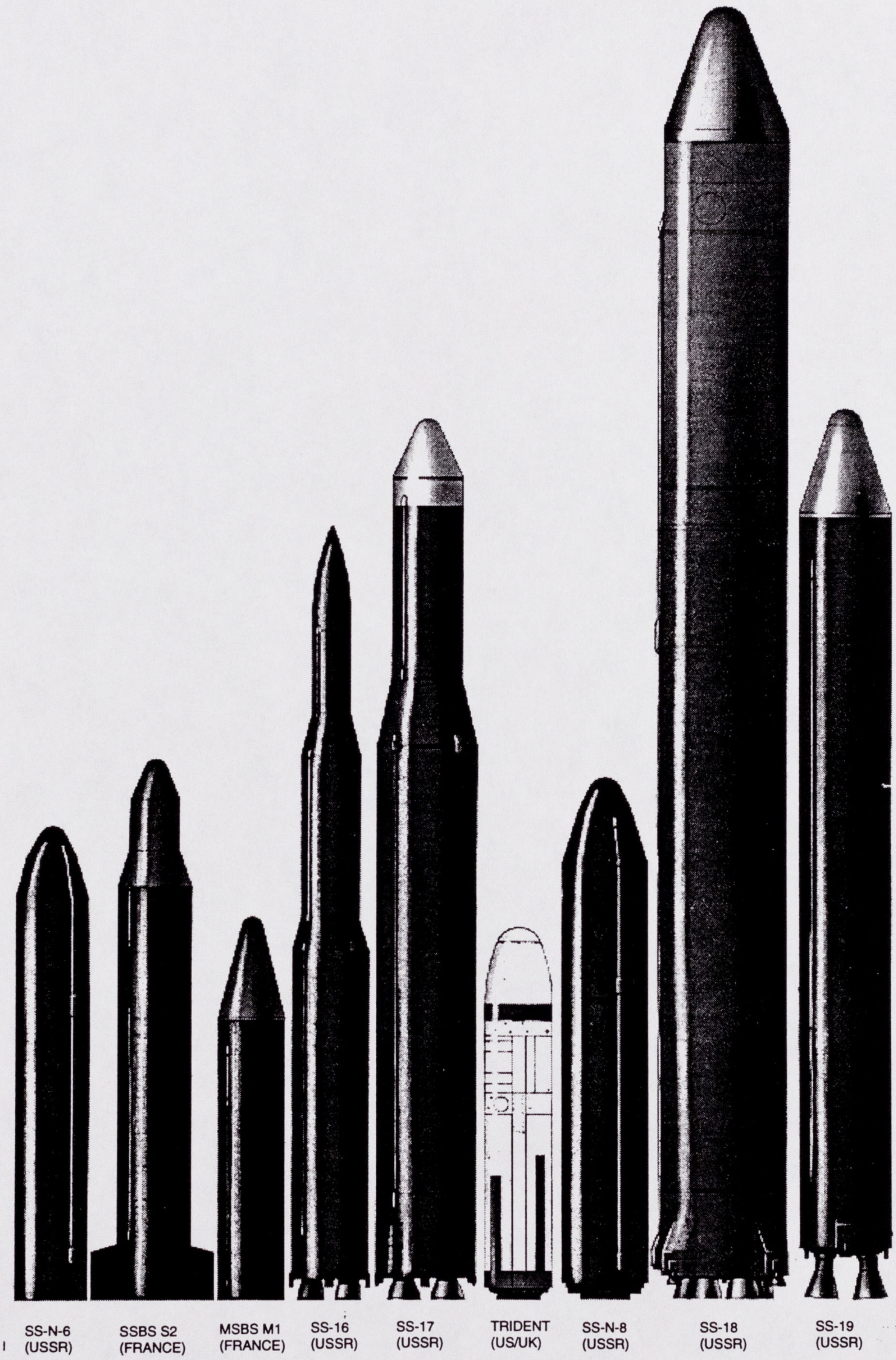


Figure A-1 Ballistic Missiles Compared

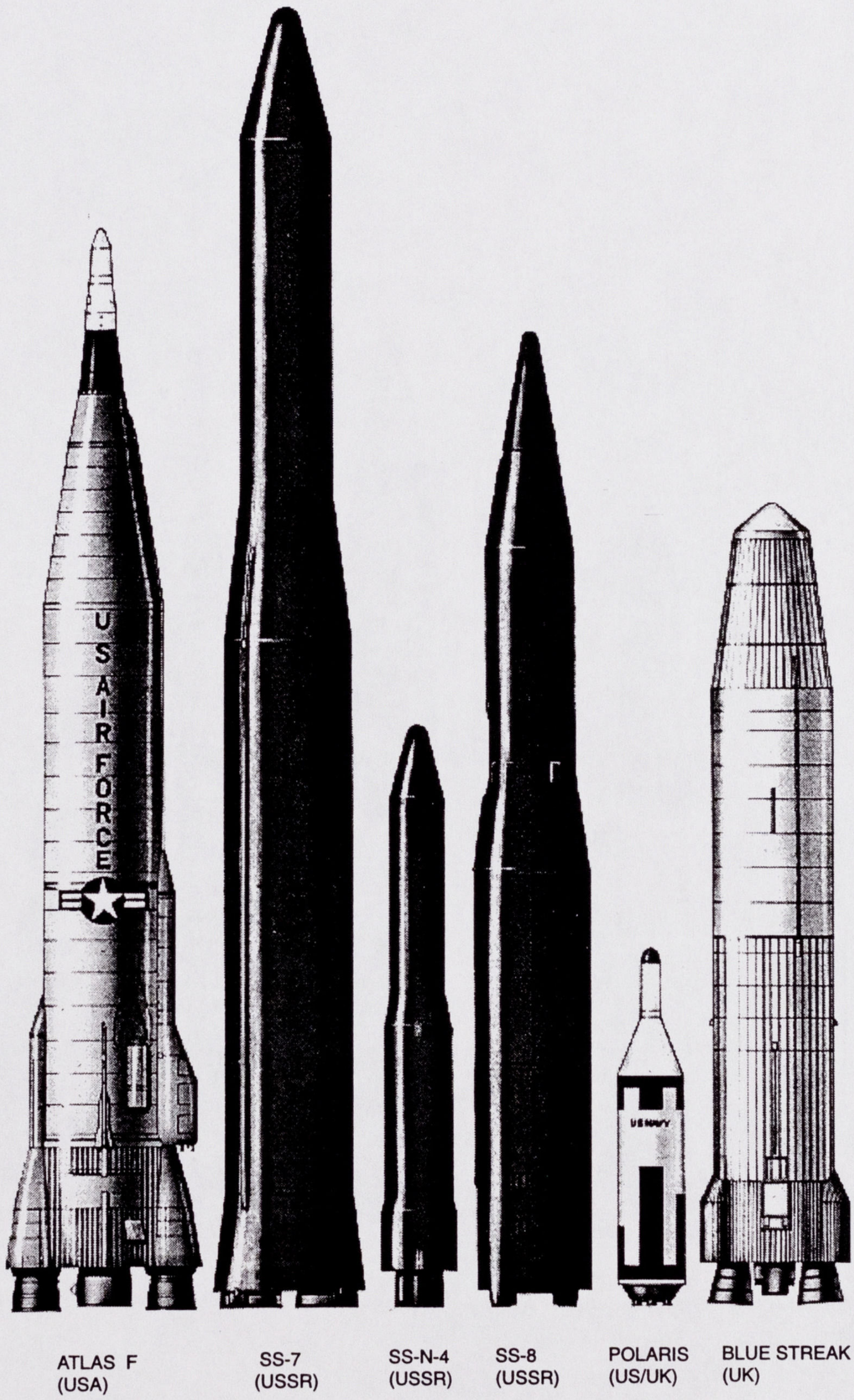


Figure A-2 Ballistic Missiles Compared

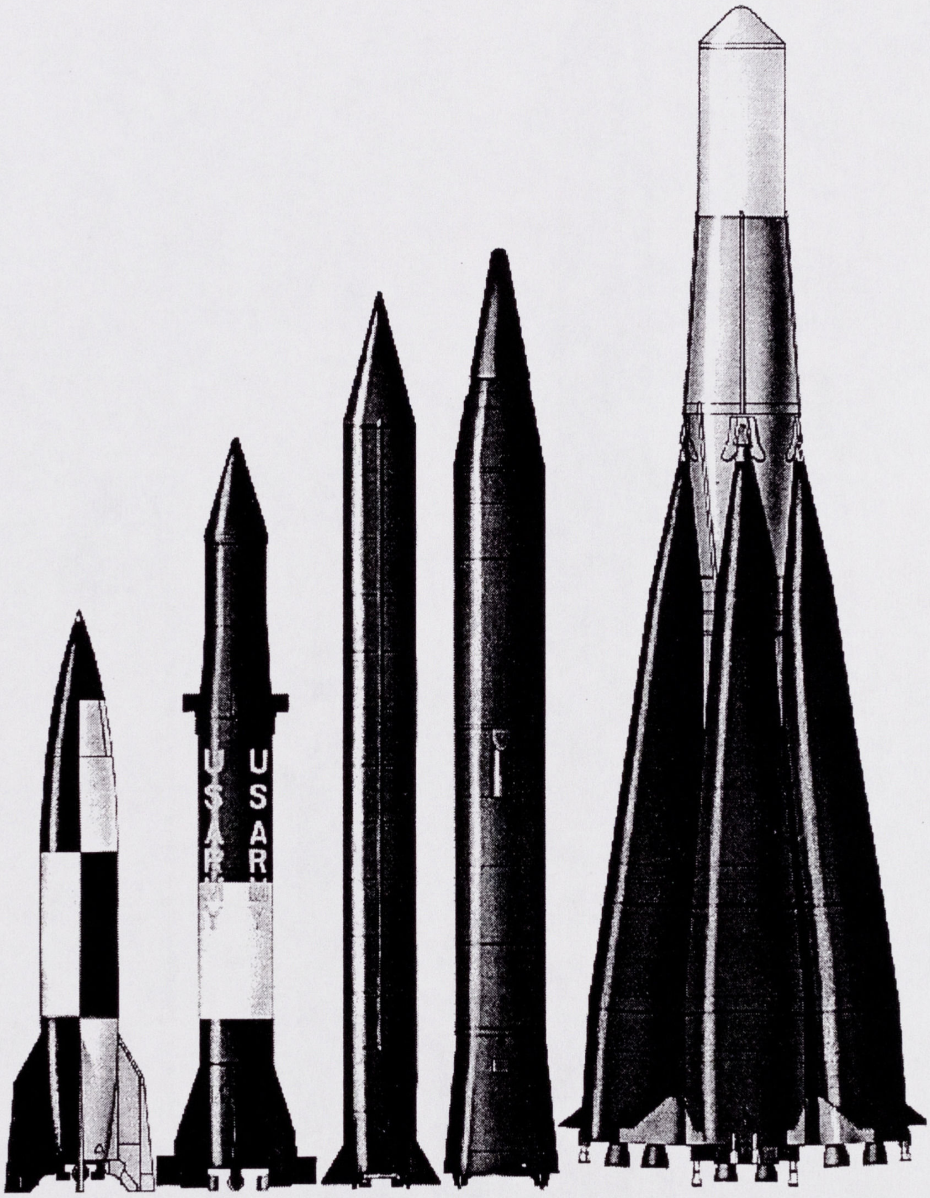


Figure A-3 Ballistic Missiles Compared

Figure A-4 Comparison of Soviet Missiles (With Details)

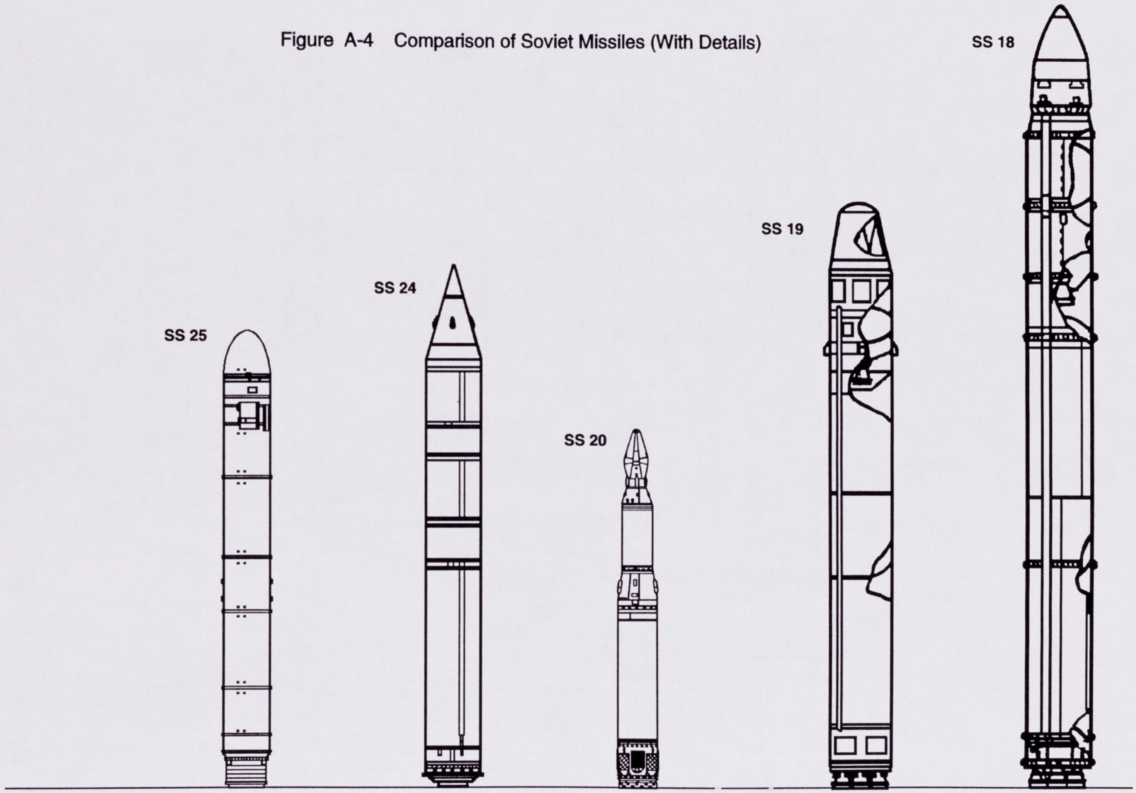


Figure A-5 Comparison of Soviet Missiles (With External Details)

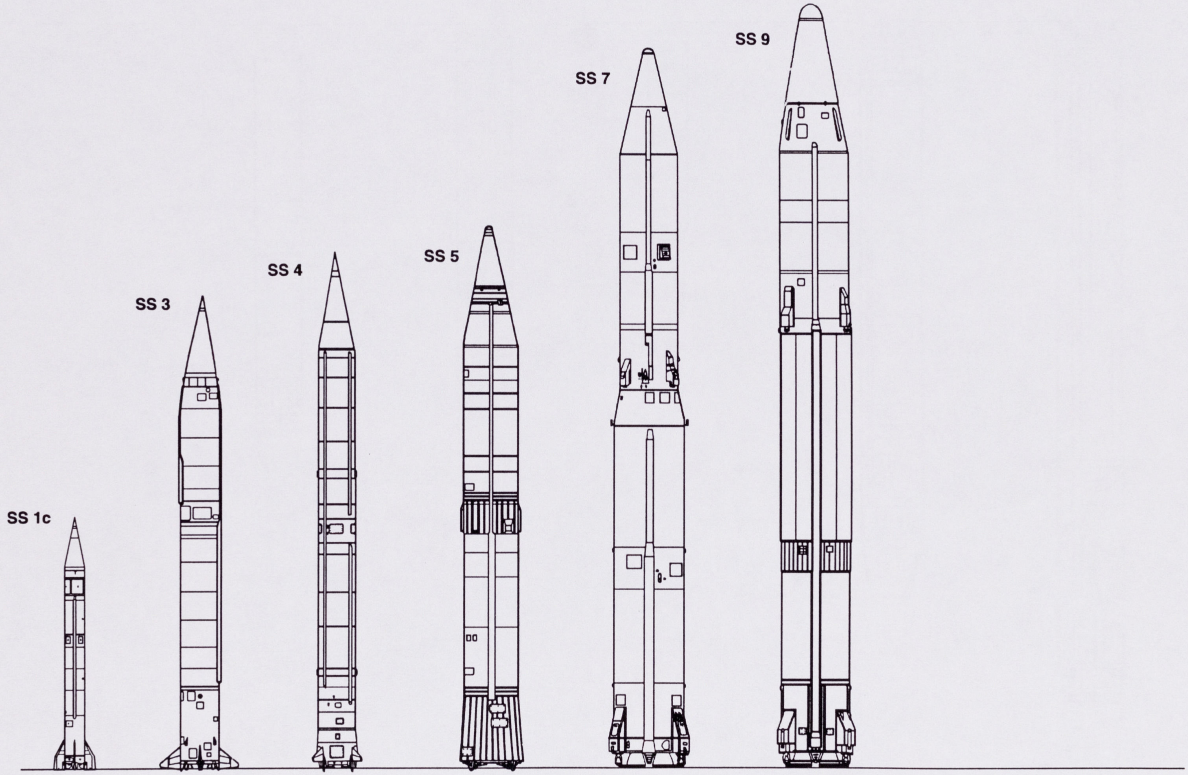
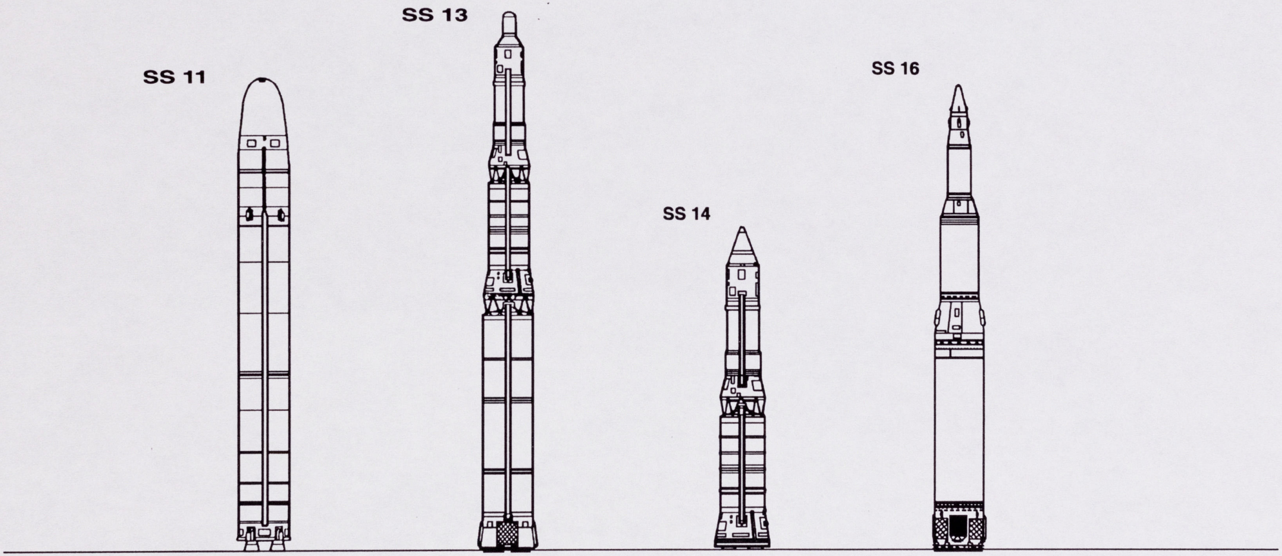


Figure A-6 Comparison of Soviet Missiles (With External Details)



A guide to ballistic missile technology. October 15-November 15, 1995. MS Ministry of Defence: DEFE 44: Directorate of Scientific Intelligence: Joint Intelligence Bureau; Division of Scientific Intelligence and Division of Atomic Energy Intelligence; Defence Intelligence Staff: Directorate of Scientific and Technical Intelligence: Reports, Notes and Memoranda DEFE 44/519. The National Archives (Kew, United Kingdom). Declassified Documents Online: Twentieth-Century British Intelligence, link.gale.com/apps/doc/FERJVW351263226/TCBI?u=omni&sid=bookmark-TCBI&pg=2. Accessed 20 Dec. 2024.